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BIOFUELS FOR TRANSPORTATION

GLOBAL POTENTIAL AND IMPLICATIONS FOR SUSTAINABLE AGRICULTURE AND ENERGY IN THE 21ST CENTURY

–FINAL REPORT–

Prepared by the Worldwatch Institute for the German Federal Ministry of Food, Agriculture and Consumer Protection (BMELV), in cooperation with the Agency for Technical Cooperation (GTZ) and the Agency of Renewable Resourcs (FNR)

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TABLE OF CONTENTS

LIST OF FIGURES, TABLES, AND SIDEBARS

LIST OF ACRONYMS

ACP	Africa, the Caribbean, and the Pacific countries
ADM	Archer Daniels Midland
ASEAN	Association of Southeast Asian Nations
BCI	BC International
BSES	Bureau of Sugar Experiment Stations
BTG	Biomass Technology Group, the Netherlands
CAFI	Consortium for Applied Fundamentals and Innovation
CAFTA	Central American Free Trade Agreement
CAP	Common Agricultural Policy of the European Union
CBI	Caribbean Basin Initiative
CDM	Clean Development Mechanism
CETESB	São Paulo State Environment Agency
CFU	World Bank Carbon Finance Unit
CNRS	Centre National de la Recherche Scientifique
CTA	Air Force Technology Center
CTC	Copersucar Technology Center
DIN	Deutsches Institut für Normung (German Standards Institute)
EBA	Everything But Arms
EEA	European Environment Agency
EEB	European Environmental Bureau
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPACT	U.S. Energy Policy Act
ESALQ	University of São Paulo's Agricultural School Luiz de Queiroz
EU	European Union
EU-ETS	European Union Emissions Trading System
FAO	Food and Agriculture Organization of the United Nations
FAPESP	Research Support Foundation of the State of São Paulo
FIPEC	Research Financing Foundation of Banco do Brazil
FSC	Forest Stewardship Council
FTPT	Tropical Foundation of Technological Research André Tosello
GBF	German Research Centre for Biotechnology
GEF	Global Environmental Facility
GFDL	Geophysical Fluid Dynamics Laboratory
GISS	Goddard Institute for Space Studies
GSP	General Systems of Preferences
GVEP	Global Village Energy Partnership
HIPC	Highly Indebted Poor Country
IAA	Institute of Sugar and Alcohol (Brazil)
IAC	Agronomic Institute of Campinas
IEA	International Energy Agency
IFIs	International Financial Institutions
IFOAM	International Federation of Organic Agriculture Movements
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Global Environment
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
KWST	Kraul & Wilkening and Stelling
MDGs	United Nations Millennium Development Goals
MERCOSUR	Mercado Commun del Sur
MOU	Memorandum of Understanding
NAFTA	North American Free Trade Agreement

NATT	Center for Absorption and Transfer of Technology
NOVEM	Dutch Energy Agency
NREL	U.S. National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of Petroleum Exporting Countries
PCF	Prototype Carbon Fund
REEEP	Renewable Energy and Energy Efficiency Partnership
RIVM	Dutch National Institute of Public Health and the Environment
RFTO	Renewable Fuel Transport Obligation
RSPO	Roundtable on Sustainable Palm Oil
SSA	Standard for Sustainable Agriculture
SAN	Sustainable Agriculture Network
SASTA	South African Sugar Technologists' Association
SRES	Special Report on Emissions Scenarios
TaTEDO	Tanzanian Traditional Energy Development and Environment Organisation
UFOP	Union zur Foerderung von Oel- und Proteinpflanzen e.V. (German union for the promotion of oil and protein plants)
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNICA	São Paulo Association of Sugar and Alcohol Manufacturers
US DOE	U.S. Department of Energy
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
VWP	Vereinigte Werkstätten für Pflanzenöltechnologie
WEC	World Energy Council
WTO	World Trade Organization
WWF	World Wide Fund for Nature/ World Wildlife Fund

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Notes to Readers

The views expressed in this study do not necessarily reflect those of the German Federal Ministry of Food, Agriculture and Consumer Protection (BMELV).

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PREFACE

The world is on the verge of an unprecedented increase in the production and use of biofuels. Rising oil prices, national security concerns, the desire to increase farm incomes, and a host of new and improved technologies are propelling many governments to enact powerful incentives for the use of these fuels, which is in turn sparking a new wave of investment.

Today, the question is not whether renewable biofuels will play a significant role in providing energy for transportation, but rather what the implications of their use will be—for the economy, for the environment, for global security, and for the health of societies. Decisions made in the next few years will help determine whether biofuels have a largely positive impact or whether the gains from biofuel use will be coupled with equally daunting consequences.

Rapidly growing interest in biofuels is being spurred by the realization that they represent the only large, near-term substitute for the petroleum fuels that provide more than 95 percent of the world's transportation energy. And today's principal biofuels—ethanol and biodiesel—have the big advantage of being easily integrated into the vast established infrastructure for petroleum fuels. As a result, biofuels now stand as a potential solution to some of the most intractable issues facing the world, including rising oil prices, increasing national and global insecurity, rising climate instability, worsening local and global pollution levels, and deepening poverty in rural and agricultural areas.

Humanity relied on bioenergy in the form of wood fuel long before oil was ever discovered. And fuels made from renewable resources, such as plant oils and sugars, have been used to power motor vehicles for more than a century. But it is only in recent years that interest in these fuels, and in the newer, "next generation" of biofuels, has exploded. Production of fuel ethanol increased 19 percent in 2005 alone, while biodiesel production jumped by 60 percent (though it represents a much smaller share of the market).[1] Among those who have joined the swelling biofuels bandwagon are farmers, national security hawks, agribusiness leaders, venture capitalists, and environmentalists.

The large ethanol industries first developed in Brazil and the United States in the 1980s have entered a new growth phase in the past few years, setting a powerful example and exporting both policy ideas and technologies around the globe. Policy makers in many countries are searching for biofuel strategies that can help them achieve a range of sometimes conflicting objectives, including boosting farm incomes, creating jobs, reducing local pollution, addressing climate change, and cutting oil imports.

Although biofuels now comprise only a small portion of the transportation fuel used globally, their production has already begun to affect commodity markets. In 2005, approximately 15 percent of the U.S. corn crop was used to provide about 2 percent of that country's non-diesel transport fuel.[2] In Brazil, about 50 percent of the sugar cane crop was dedicated to producing about 40 percent of the non-diesel transport fuel, and in Europe, more than 20 percent of the rapeseed crop was tapped to provide about 1 percent of all transport fuel.[3] Among the other countries that have made major commitments to biofuels in recent years are China, Colombia, India, the Philippines, and Thailand.

In order to assess the ramifications of the large-scale development of biofuels around the globe, the German Federal Ministry of Consumer Protection, Food and Agriculture (BMELV) has commissioned the German Agency for Technical Cooperation (GTZ) and the Worldwatch Institute to undertake a comprehensive survey of biofuels for transportation, guided by the principles of sustainable agriculture, energy, and transport. Building on the input from detailed country studies from Brazil, China, Germany, India, and Tanzania, this report aims to bring the results of focused analysis into the wider international debate.

This report is intended as a resource for decision makers, describing existing production methods and policies for biofuels and assessing options for their future development. Parts 1 and 2 discuss current and future feedstock options, production technologies, and potentials. Parts 3 and 4 address key economic, social, and environmental concerns that will be raised by the large-scale production of biofuels. Part 5 details the fuel, engine, vehicle, and infrastructure technologies that may be deployed to facilitate greater use of biofuels in the world's transportation fuel markets. Part 6 assesses the various policy frameworks being used to promote biofuels, as well as new ideas under active discussion. Part 7 describes the current and future outlook for biofuels in Germany and Europe, and Part 8 provides recommendations for decision makers.

While the potential market for biofuels is enormous, this report concludes that a wide range of issues remain to be addressed. In particular, the transition from extracting oil from beneath the ground to cultivating fuel feedstock on the surface could lead to competition for scarce resources and place additional strain on Earth's already-stressed life-support systems. The convergence of the energy, food, and fiber markets will further complicate global investment decisions and will likely increase food prices—a trend that could be beneficial to farmers, but could make it more difficult to satisfy the food needs of the world's urban poor. Additionally, if farmers are pushed to expand their cropping into new territory to meet growing biofuel demand, this could result in soil erosion, aquifer depletion, and the loss of biologically rich ecosystems, including tropical forests. Government policy decisions, and the resolve to see them properly implemented, will be critical in determining the net ecological impacts of expanded biofuel use.

The report also finds that the potential benefits of biofuels will be realized only if a host of new environmentally sustainable technologies are employed, ranging from new crops and farming methods to advanced conversion technologies and highly efficient vehicles. One of the most important and anticipated innovations is the development of cellulosic ethanol derived from plant stalks, leaves, and even wood. Synthetic diesel, made from an even broader range of energy crops or waste streams, also holds great promise. These technologies, which are close to being introduced commercially, will make it possible to produce biofuels from agricultural and forestry wastes, as well as from non-food crops such as switchgrass that can be grown on degraded lands. Wise and innovative policies will be needed to steer the biofuel industry in these directions.

The broader social and economic impacts of biofuels will likewise be determined largely by policy decisions. One of the great promises of biofuels—and the main political engine behind them—is to increase farm incomes and strengthen rural economies. Indeed, if farmers not only produce our food and fiber, but also a growing portion of our energy, biofuels could transform agriculture more profoundly than any development since the green revolution. Since biofuel feedstock must be gathered across wide areas, they will never be as centrally produced as petroleum products are. However, as the market grows and biofuels become a large-scale commodity, an increasing share of the income will likely go to larger farms and agribusinesses. Conscious decisions will need to be made if smaller-scale biofuel production is to be successful. The ability of small farmers to benefit from biofuels will also be determined in part by broader decisions about land reform and tax policies.

Another potential benefit of biofuels is the role they could play in reducing the threat of global climate change. The transportation sector is responsible for about one-quarter of global energy-related greenhouse gas (GHG) emissions, and that share is rising. At least for the near term, biofuels combined with energy-efficiency improvements offer the only option for dramatically reducing demand for oil and associated transport-related warming emissions. But while a dramatic increase in biofuel production and use could reduce emissions from transport significantly, there is also the possibility that such a ramping up could intensify the threat of a warming world. The overall climate impacts of biofuels will depend on several factors, the most important being changes in land use, choice of feedstock, and management practices. The greatest potential for reducing GHG emissions lies in the development of next-generation biofuel feedstock and technologies.

International trade and the rules that govern it will play a major role in shaping biofuel development. To date, biofuels have been nurtured by national policies that favor domestically produced biofuels at the expense of imports. Domestic production can replace expensive oil imports, help unburden developing countries from staggering energy import bills, stabilize their currencies, and encourage foreign investment. However, such domestically oriented policies are now limiting the development of the international biofuel market. Brazil, in particular, hopes to turn ethanol into a major export business. Such trade will undoubtedly serve as a tremendous spur to biofuel development, particularly in tropical countries blessed with inexpensive sugar cane and plant oils. A global biofuel market could serve to stabilize supply with staggered harvests and to smooth out variations in yield across climatic zones and hemispheres. But such a market could also discourage biofuel development in poorer countries and those with less favorable growing conditions.

This report concludes that biofuels have a large potential to substitute for petroleum fuels and, together with a host of other strategies, including the development of far more efficient vehicles, can help the world achieve a more diversified and sustainable transportation system in the decades ahead. However, these promises will only be achieved if policies are enacted that steer biofuels in the right direction—policies that will need to be adjusted and refined as the state of knowledge advances and as the risks and opportunities of biofuel development become clearer.

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EXECUTIVE SUMMARY

Biofuels: Current Status and Global Potential

The production and use of biofuels have entered a new era of global growth, with both the scale of the industry and the number of countries involved reaching unprecedented levels. Surging investment in biofuel production is being driven by a variety of factors, including the development of more efficient conversion technologies, the introduction of strong new government policies, and, of course, the rising price of oil. Underlying the growing commitment of governments to biofuel development is the desire to find new markets for farmers and their products and to reduce both petroleum imports and emissions of carbon dioxide and other gases that are contributing to global warming.

The two primary biofuels in use today are ethanol and biodiesel, which can both be used in existing vehicles. Ethanol is readily blended with gasoline, and biodiesel is blended with petroleum-based diesel for use in conventional diesel-fueled vehicles. Ethanol currently accounts for more than 90 percent of total biofuels production, with biodiesel making up the rest. Global fuel ethanol production more than doubled between 2000 and 2005, while production of biodiesel, starting from a much smaller base, expanded nearly fourfold. By contrast, world oil production increased by only 7 percent during the same period.

Since the 1970s, Brazil has been at the forefront of efforts to produce ethanol from sugar cane, the leading feedstock to date. Three decades of government support and private investment have allowed Brazil to steadily improve the efficiency of its production processes and to make ethanol economical for consumers. During the same period, the United States has been the leader in turning grains (mainly corn) into ethanol fuel, improving efficiency and lowering costs.

Germany has been the leader in biofuel production in Europe, in particular the large-scale production of biodiesel fuel from the oil of rape and sunflower seeds. Thanks to government support starting in the early 1990s, the country was producing about half of the world's biodiesel by 2005, with production continuing to expand rapidly.

The recent pace of advancement in technology, policy, and investment suggest that the rapid growth of biofuel use could continue for decades in the future and that these fuels have the potential to displace a significant share of the oil now consumed in many countries. A recent study found that advanced biofuel technologies could allow biofuels to substitute for 37 percent of U.S. gasoline within the next 25 years, with the figure rising to 75 percent if vehicle fuel efficiency were doubled during the same period. The biofuel potential of EU countries is in the range of 20–25 percent of fuel needs if strong sustainability criteria for land use and crop choice are assumed, and bioenergy use in non-transport sectors is growing in parallel.

Despite the large-scale, long-term potential of biofuels made from cellulosic feedstock, in the near-term, the current generation of biofuels is expected to predominate. The potential for these biofuels is particularly large in tropical countries, where high crop yields and lower costs for land and labor—which dominate the cost of these fuels—provide an economic advantage that is hard for countries in temperate regions to match. Sugar cane is especially productive. When petroleum prices are above €41 ($50) per barrel, as they were for most of 2005 and early 2006, ethanol from sugar cane is less expensive than gasoline. It has been estimated that worldwide sugar cane production could be expanded to a level such that this crop alone could displace about 10 percent of gasoline use worldwide. This would allow scores of low-income countries to become significant producers—and potentially exporters—of a valuable new commodity.

This report concludes that biofuels have a large potential to substitute for petroleum fuels, which, together with a host of other strategies, including the development of far more efficient vehicles, can help the world achieve a more diversified and sustainable transportation system in the decades ahead. However, these promises will only be achieved if policies are enacted that steer biofuels in the right direction—policies that will need to be adjusted and refined as the state of knowledge advances and as the risks and opportunities of biofuel development become clearer.

In the coming years, the international development of biofuels and bio-based co-products has the potential to increase energy security for many nations; to create new economic opportunities for people in rural, agricultural areas the world over; to protect and enhance the environment on local, regional, and global scales; and to provide new and improved products to millions of consumers. Key to shaping such a future, in which biofuels are produced sustainably and used on a large scale, is defining clear goals and enacting the policies necessary to achieve them.

New Technologies, Crops, and Prospects

The various biomass feedstock used for producing biofuels can be grouped into two basic categories: the currently available “first-generation” feedstock, which are harvested for their sugar, starch, and oil content that can be converted into liquid fuels using conventional technology; and the “next-generation” cellulosic biomass feedstock, which are harvested for their total biomass and whose fibers can be converted into liquid biofuels only by advanced technical processes.

Cellulosic biomass such as wood, tall grasses, and crop residues are expected to significantly expand the quantities and types of feedstock available for biofuel production in the future, as new conversion technologies are developed that enable the production of fuels from these materials. Cellulosic biomass is much more abundant than food crops, and can be harvested with less direct interference in the food economy and potentially less strain on land, air, and water resources. Promising energy crops include fast-growing woody crops such as willow, hybrid poplar, and eucalyptus, as well as tall perennial grasses such as miscanthus and switchgrass.

Over the next 10–15 years, it is expected that lower-cost sources of cellulosic biomass (e.g. the organic fraction of municipal waste, biomass processing residues, crop residues, and forest residues) will provide the first influx of next generation feedstock, with cellulosic energy crops expected to begin supplying feedstock for biofuel production toward the end of this period, then expanding rapidly in the years beyond.

For biofuels to reach their full potential in meeting future transportation needs, it is critical that economically competitive technologies that can convert cellulosic biomass resources into liquid biofuels be developed and deployed. Substantial progress has been made in developing advanced enzymes that can readily convert cellulosic material into sugars that can then be fermented into ethanol. Technologies are also being developed to reduce the cost of producing a diesel fuel alternative from cellulosic biomass using thermal biomass gasification technology coupled with a Fischer-Tropsch conversion system.

It is expected that the combination of cellulosic biomass resources and next-generation biofuel conversion technologies will be able to fully compete with conventional gasoline and diesel fuel without subsidies within the coming decades.

Estimates of the longer-term potential for harnessing biomass energy range widely and depend on factors such as the extent to which the yields of both food and energy crops can increase, the size of the human population, and the per capita human demand for food and land. Theoretically, biomass supplies could be huge, rivaling current oil supplies.

Key Economic and Social Issues

Petroleum is a highly concentrated energy resource, and the world's current transportation systems are almost completely dependent on it. This has left the world economy at risk if oil supplies were disrupted in any of the relatively few countries that are significant oil exporters. Concentrated wealth, social tensions, and inadequate political institutions have left many of these countries as less than secure suppliers of the world's most vital commodity. Biofuels will bring a much broader group of countries into the liquid fuel business, thereby diversifying supplies and reducing the risk of disruption. And because they can be produced in most regions of the globe, the risks inherent in transporting these fuels long distances will also be reduced. In the long run, this is likely to help stabilize fuel prices.

The growth in demand for biofuels offers an unprecedented opportunity to support agricultural industries and provide jobs in rural communities. Such economic development has been the primary motivation for biofuel programs in nearly all cases so far, where the market for transportation fuel offers a solution for overproduction. As a refined product, biofuels offer an additional opportunity to add value to raw agricultural goods. Although historically farmers in most countries have not gained substantially from agricultural value-adding processes, policmakers can learn from the lessons of the past and guide nascent biofuel industries in the direction of greater farmer ownership.

Large-scale production of biofuels will tend to increase the price of agricultural commodities. This can benefit farmers but will hurt those who can barely afford food, as well as agricultural processors and the meat industry. However, the situation is more nuanced than many have portrayed it: for example, the meat industry will benefit from the increased production of high-protein feeds that are the co-products of corn ethanol, soybean biodiesel, and other biofuel production. And many of the world's hungry are also farmers. The poorest people will benefit more from the cultivation of biofuels if they are involved in the "value-added" stages of their production, such as processing and refining. In remote areas, poor farmers could benefit by producing their own fuels.

Many of the countries that consume large quantities of transportation fuels have limited land available for producing biomass feedstock, which leaves them unable to produce more than a fraction of their transportation fuels from domestic biomass. This will likely encourage many industrial countries to consider importing biofuels and to push for elimination of the tariffs and other trade barriers that have so far limited biofuel trade. Ongoing WTO negotiations aimed at liberalizing trade in agricultural commodities are likely to spur the move to freer trade in biofuels, offering an opportunity for countries to provide new agricultural revenues as an offset to the loss of trade-distorting agricultural subsidies.

Environmental Issues

Petroleum fuels have exacted a heavy environmental toll on the planet, and their impact is likely to worsen as dirtier and more remote supplies are tapped. As an alternative, biofuels offer the opportunity to reduce the emissions of both greenhouse gases and urban air pollutants. Their cultivation could cause huge disruptions in land use, but, if managed properly, the cultivation of energy crops could also facilitate the sequestration of carbon in the soil and the protection and restoration of ecosystems otherwise degraded by human activities.

One of the largest questions raised about biofuels is their net energy balance, particularly the question of whether the bio-based fuels produced contain more useful energy than the fossil fuels required to make them. This was a greater concern a decade ago than it is today, since advances in technology have improved production efficiency, giving virtually all current commercial biofuels a positive fossil energy balance. Plants use photosynthesis to convert solar energy into chemical energy, and as technologies improve, the amount of fossil fuels used to produce the crops and convert them to biofuels will continue to decline.

Biofuels have great promise for reducing the transport sector's contribution to global climate change. Today, transportation is responsible for 25 percent of the world's energy-related greenhouse gas emissions, and that share is rising. A dramatic increase in the production and use of biofuels has the potential to significantly reduce those emissions, particularly with the development of advanced biomass technologies that rely on agricultural wastes and dedicated cellulosic crops such as switchgrass. However, if biofuels are produced from low-yielding crops and are grown with heavy inputs of fossil energy on previously wild grasslands or forests, they have the potential to generate as much or more greenhouse gas emissions than petroleum fuels do.

Biofuel production offers similar risks and opportunities with regard to the health of the world's ecosystems. Expanding the cultivation of biofuel crops has the potential to contribute to soil depletion and erosion, habitat loss, and reduced biodiversity. On the other hand, cellulosic biofuels could be produced from perennial grasses and trees that protect lands vulnerable to erosion and restore lands degraded by overuse. By diversifying monoculture ecosystems, such crops could also serve to increase local biodiversity. For these benefits to be realized, the expansion of biofuel production will need to be accompanied by a new generation of clear and strict land-use laws, particularly in countries with tropical forests that are at risk of destruction.

Replacing a portion of petroleum fuel with a biofuel generally brings a reduction in vehicle emissions of sulfur, particulates, and carbon monoxide. However, particularly in engines poorly calibrated to run on biofuels, nitrogen oxide emissions can increase, and in low-level blends with gasoline, ethanol can cause increased emissions of volatile organic compounds. Increasingly stringent standards for petroleum-based fuels will tend to reduce the emissions advantages offered by conventional biofuels, but the next generation of biofuels, including Fischer-Tropsch diesel, can be tailored to meet certain emission specifications. In developing countries, ethanol and biodiesel could play a significant role in improving urban air quality and helping to phase out lead-based and otherwise toxic fuel additives.

Market Introduction and Technology Strategies

The trend in biofuel production has been toward larger-scale conversion facilities. This is likely to continue, particularly since future facilities for converting lignocellulosic feedstock into biofuels are expected to be even larger (and more capital-intensive), and significant economy-of-scale advantages are expected to reduce the cost of production. However, the relatively dispersed nature of crops and the high cost of transporting solid biomass will put upper limits on the future scale of biofuel plants. Farmers will be less likely to have ownership in production facilities if trends towards more capital intensive, large-scale plants continue.

In order to be added to fuel tanks and combusted in vehicle engines, biofuels must be processed to consistent standards, though warmer temperatures tend to allow a larger margin for error. Vehicle manufacturers typically warrantee ethanol blends of 10 percent or less with gasoline in conventional spark-ignition engines. Specially designed flex-fuel vehicles can run on a range of ethanol-gasoline blends. Biodiesel blends of as high as 20 percent are authorized in the warrantees for most compression-ignition engines, and in a few instances warrantees allow 100 percent biodiesel. Other biofuels, such as straight vegetable oil, methanol, DME, and biogas require more extensive engine modifications.

Biofuels can generally be distributed via the petroleum distribution infrastructure, though in some cases special measures must be taken. Ethanol has a high affinity for water, which can cause it to separate from gasoline. For this reason, colder climates may require dedicated ethanol pipelines, which are the cheapest means of fuel distribution. And because of the relatively high solvency of ethanol and biodiesel, their introduction into tanks and facilities previously used only for petroleum-based fuels may initially cause a release of deposits left by gasoline and diesel.

With its success in commercializing sugar cane ethanol, Brazil has accumulated a reservoir of experience that will prove valuable for countries developing new biofuel programs. As other countries develop expertise in cultivating new crops and utilizing new technologies for converting these into fuels, they can expedite both the displacement of petroleum and global economic development by sharing their knowledge. This interchange of technology and ideas offers an opportunity to promote the sustainable use of biofuels. As the next generation of these fuels is developed, it will be important to develop efficient systems for harvesting, pre-processing, and delivering new types of feedstock to processing facilities.

Policy Recommendations

To achieve a rapid scaling-up in biofuel production that can be sustained over the long term, governments must enact a coordinated set of policies that are consistent, long-range, and informed by broad stakeholder participation.

Supportive government policies have been essential to the development of modern biofuels over the past two decades. Blending mandates, tax incentives, government purchasing policies, and support for biofuel-compatible infrastructure and technologies have been the most successful in fostering biofuel production. Countries seeking to develop domestic biofuel industries will be able to draw important lessons—both positive and negative—from the industry pioneers: Brazil, the United States, and the European Union.

Efforts to commercialize new energy crops will require particular attention from governments, many of which already possess national agricultural policies that have a significant impact on the choice of which crops to grow. Government policies can help assure that particular crops are grown on lands that are appropriate for them. For example, perennial grasses for biofuel production may be grown on erosion-prone land that would be inappropriate for annual row crops. The environmental benefits of energy crop production can be "monetized" with the help of government programs, such as payments or tradable credits for benefits such as reduced runoff of soil and agro-chemicals into streams, and greenhouse gas benefits related to increased storage of carbon in soils.

In the future, biofuel promotion policies should be tied to criteria that ensure sustainable harvesting methods and equitable distribution of production revenues. They should also be crafted in the context of larger transportation goals: reducing petroleum subsidies and increasing the taxes on petroleum are indirect ways to promote biofuels while also helping to lessen the use of oil. Measures to increase efficiency remain the cheapest way to alleviate the pollution and security risks associated with petroleum use.

As biofuels are increasingly traded across international boundaries, biofuel standards can help ensure that the industry develops without exploiting laborers or degrading the resource base. Initially, these standards can be based on existing certification schemes for forestry and farming practices. It is important that such ecological and social standards not be unduly burdensome on infant biofuel industries, nor should they be surreptitious trade barriers. Encouraging international and regional biofuel standards, and offering technical assistance to developing countries with nascent biofuels industries, can help to eliminate entry hurdles and encourage environmental, economic, and social benefits from increased sustainable biofuel trade.

The emerging biofuel industry also faces challenges in obtaining financing for the first risky, commercial-scale systems for producing biofuels from cellulosic biomass. If governments and international financial institutions wish to speed the commercialization of these next-generation fuels, they will need to provide financing and take other actions to help reduce financial risks, in order to help the industry move quickly through early commercialization barriers. Joint public-private demonstration projects could play an important role in developing experience along biomass production chains where many questions still remain.

The large variety of vegetable oils and animal fats that can be used for biodiesel production, and the variability in fuel characteristics that can occur with biodiesel produced from this feedstock, means that fuel quality specifications require particularly close attention for biodiesel. Germany and the United States have developed their own unique biodiesel standards and are continuing to work to improve these standards. With worldwide demand for biodiesel escalating rapidly, there is a growing need for international collaboration on biodiesel standards and fuel quality in order to facilitate trade.

Collaboration between industry and government will be essential to ensuring that sustainable feedstock supplies are developed. In addition, some form of certification will be needed to verify the sustainability of feedstock production. This is particularly true with regard to greenhouse gas impacts, where countries are working to achieve measurable, verifiable reductions in carbon emissions. Based on lessons learned from organizations such as the Forest Stewardship Council, the approach used to establish policies and standards for feedstock sustainability should be transparent, independent, and participatory—and it should not be used as a Trojan horse for introducing trade barriers.

It is also essential that governments promote biofuels within the context of a broader transition to a more efficient, less polluting and more diversified global transport sector. These fuels must be part of a portfolio of options that includes dramatic improvements in vehicle fuel economy, investments in public transportation, better urban planning, and smarter and more creative means of moving around a village or across the globe. In combination with improved vehicle efficiency, smart growth, and other new fuel sources such as biogas—and eventually even renewable hydrogen or electricity—biofuels can drive the world towards a far less vulnerable and less polluting transport system.

Key overarching recommendations for accelerating the development of biofuels, while maximizing the benefits and minimizing the risks, include:

- **Strengthen the Market**. Biofuel policies should focus on market development. An enabling environment for renewable fuel industry development must be created in order to draw in entrepreneurial creativity, private capital, and technical capacity.

- **Speed the Transition to Next-Generation Technologies.** Policies are needed to expedite the transition to the next generation of feedstock and technologies that will enable dramatically increased production at lower cost, combined with the real potential for significant reductions in environmental impacts.

- **Protect the Resource Base.** Maintenance of soil productivity, water quality, and myriad other ecosystem services is essential. The establishment of national and international environmental sustainability principles and certification is important for protecting resources as well as maintaining public trust in the merits of biofuels.

- **Facilitate Sustainable International Biofuel Trade.** The geographical disparity in production potential and demand for biofuels will necessitate the reduction in barriers to biofuel trade. Freer movement of biofuels around the world should be coupled with social and environmental standards and a credible system to certify compliance.

- **Distribute Benefits Equitably.** This is necessary in order to gain the potential development benefits of biofuels. Enabling farmers to share ownership throughout the production chain is central to this objective.

PART I. STATUS AND GLOBAL TRENDS

Chapter 1. Current Status of the Biofuel Industry and Markets

1.1 A Global Overview

The liquid biofuels most widely used for transport today are ethanol and biodiesel. Ethanol is currently produced from sugar or starch crops, while biodiesel is produced from vegetable oils or animal fats. The growth in the use of biofuels has been facilitated by their ability to be used as blends with conventional fuels in existing vehicles, where ethanol is blended with gasoline and biodiesel is blended with conventional diesel fuel.

Ethanol currently accounts for more than 90 percent of total biofuel production.[1] About one-quarter of world ethanol production goes into alcoholic beverages or is used for industrial purposes (as a solvent, disinfectant, or chemical feedstock); the rest becomes fuel for motor vehicles.[2] Most of the world's biodiesel, meanwhile, is used for transportation fuel, though some is used for home heating.

Global fuel ethanol production more than doubled between 2000 and 2005, while production of biodiesel, starting from a much smaller base, expanded nearly fourfold.[3] (See Figures 1–1 and 1–2.) In contrast, oil production increased by only 7 percent over this period. (In absolute terms, however, world petroleum production increased by some 360 million liters a year from 2000–05, compared to some 19 million liters for ethanol.[4]) In 2005, ethanol comprised about 1.2 percent of the world's gasoline supply by volume, and about 0.8 percent by transport distance traveled.[5]

Figure 1–1. World Fuel Ethanol Production, 1975–2005

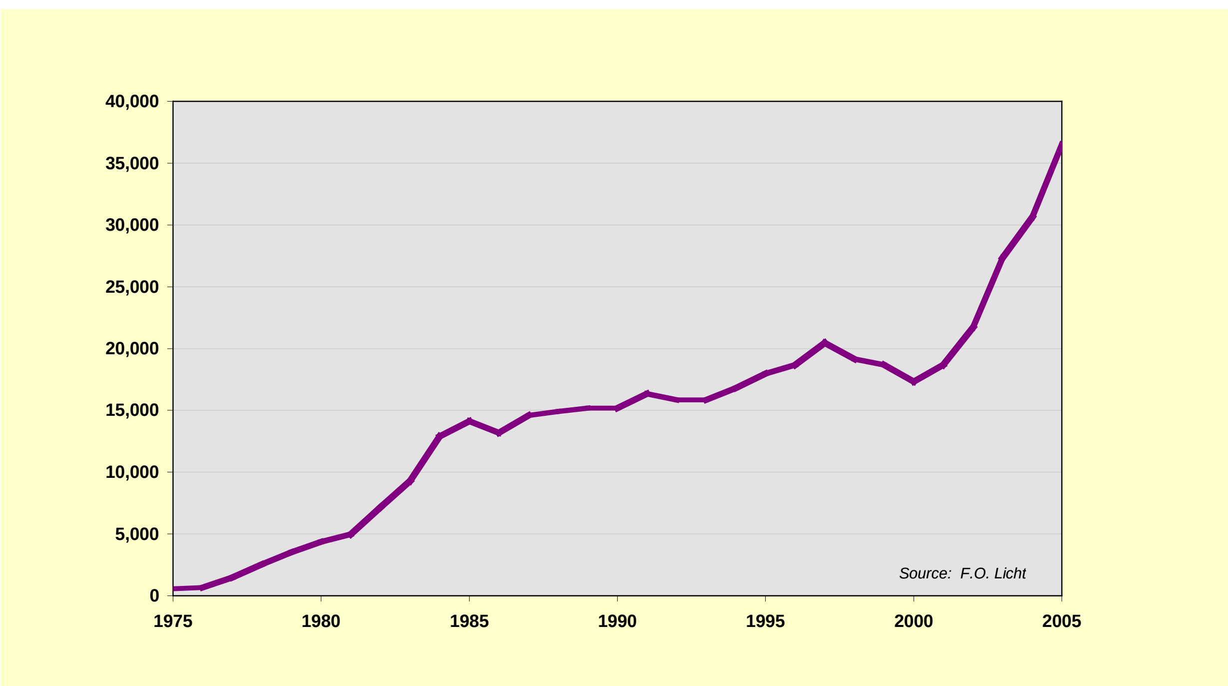
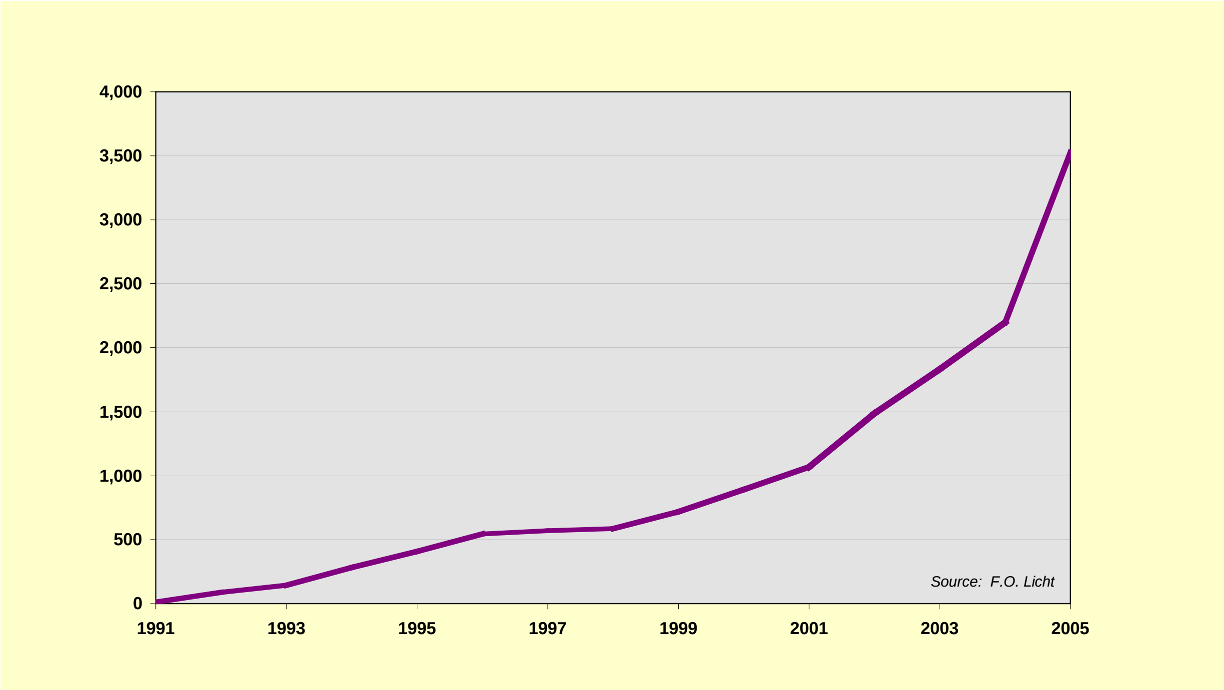


Figure 1–2. World Biodiesel Production, 1991–2005



1.2 History of Biofuel Production Programs

Biofuels have been used in automobiles since the early days of motorized transport. American inventor Samuel Morey used ethanol and turpentine in the first internal combustion engines as early as the 1820s. Later that century, Nicholas Otto ran his first spark-ignition engines on ethanol, and Rudolph Diesel used peanut oil in his prototype compression-ignition engines. Henry Ford's Model T could even be calibrated to run on a range of ethanol-gasoline blends. However, just as automobiles were becoming popular at the beginning of the 1900s, the fuel market was flooded with cheap petroleum fuels.[6]

Biofuels represented only a small proportion of total fuel during the early 20th century. They were supported by policies in several European countries, especially France and Germany, where at times they neared 5 percent of the fuel supply. In tropical areas with irregular supplies of petroleum and in enclosed settings such as mines, biofuels were often the favored fuel; during World Wars I and II, ethanol was also used to supplement petroleum in Europe, the United States, and Brazil. However, military demobilization in the post-war period and the development of new oil fields in the 1940s brought a glut of cheap oil that virtually eliminated biofuels from the world fuel market.[7]

The oil crises of the 1970s prompted countries to again seek alternatives to imported oil. Brazil, which had maintained a small fuel ethanol industry since the 1930s, expedited a national ethanol program called Proálcool with an eye to alleviating its great national debt and expanding its agricultural industry. Especially after the second oil crisis of 1979, when oil prices reach their historic zenith, the Brazilian government prioritized ethanol production, supporting expanded sugar cane acreage, new ethanol distilleries, and ethanol-only cars. By the mid-1980s, ethanol was displacing almost 60 percent of the country's gasoline.[8]

Also motivated by the high and volatile oil prices of the 1970s, the United States launched its own fuel ethanol program at the end of the decade, using corn to produce a proportionally small but increasing amount of ethanol. The Brazilian and U.S. ethanol industries still produce the vast majority of the world's fuel ethanol—almost 90 percent in 2005.[9]

The oil crises prompted other countries to promote biofuels as well, though these efforts were less successful. In China, the government encouraged peasants to cultivate oil plants that would provide insurance against disruptions in the supply of diesel fuels, but it abandoned these efforts after the price of oil fell in the mid-1980s.[10] In 1978, the Kenyan government initiated a program to distill ethanol from sugar cane, mixing it in a 10 percent blend with gasoline, but this program faltered due to drought, poor infrastructure, and inconsistent policies.[11] Zimbabwe and Malawi initiated larger programs in 1980 and 1982, respectively, but only Malawi has consistently produced fuel ethanol since then.[12]

In Europe, a trade dispute triggered a rise in biodiesel production starting in 1992. The European Union (EU) agreed to prevent gluts in the international oilseeds market by confining production to just under 5 million hectares. European governments helped create a new market for farmers on the remaining "set-aside" land, primarily by reducing the taxes on biodiesel—a policy that has led to a rapid increase in European biodiesel production, particularly in Germany[13]

More recently, environmental standards have become important drivers for biofuel markets. In the United States, the Environmental Protection Agency began requiring cities with high ozone levels to blend gasoline with fuel oxygenates, including ethanol. When state governments learned in the late 1990s and early 2000s that the most common oxygenate, methyl tertiary-butyl ether (MTBE), was a possible carcinogen that was seeping into groundwater, 20 states passed laws to phase it out, creating a surge in demand for U.S. ethanol in the early 2000s.[14]

In Brazil, the auto industry's 2003 introduction of so-called "flexible-fuel" vehicles (FFVs), which can run on any combination of gasoline or ethanol, has given drivers the freedom to choose whichever of the fuels is cheaper. Consumer demand for these vehicles has surged, and by early 2006, more than 75 percent of new cars sold in the country were FFVs.[15] Combined with high petroleum prices, these cars have led to a dramatic increase in Brazilian ethanol production.[16]

1.3 Current Biofuel Production

Brazil and the United States dominate world ethanol production, which reached a record 36.5 billion liters in 2005.[17] (See Table 1–1.) Close to half the world's ethanol fuel was produced in Brazil in 2005, where sugar cane grown mostly in its center-south region provides roughly 40 percent of the country's non-diesel fuel.[18] Almost as much ethanol was produced in the United States, nearly all of it from corn crops grown in the northern Midwest, although this represents only 2–3 percent of the country's non-diesel fuel.[19]

The remainder of ethanol production comes primarily from the European Union, where Spain, Sweden, France, and Germany are the big producers, using mainly cereals and sugar beets. China uses corn, wheat, and sugar cane as feedstock to produce a large amount of ethanol destined mostly for industrial use. In India, sugar cane and cassava have been used intermittently to produce fuel ethanol.[20]

Table 1–1. World Fuel Ethanol Production, 2005

Country or Region	Production (million liters)	Share of Total (percent)
Brazil	16,500	45.2
United States	16,230	44.5
China	2,000	5.5
European Union	950	2.6
India	300	0.8
Canada	250	0.7
Colombia	150	0.4
Thailand	60	0.2
Australia	60	0.2
World Total	**36,500**	**100.0**

Source: See Endnote 17 for this chapter.

In 2005, many new ethanol production facilities began operating, were under construction, or were in the planning stage. For example, U.S. ethanol production capacity increased by nearly 3 billion liters during 2005, with an additional 5.7 billion liters of new capacity under construction going into 2006.[21]

Biodiesel has seen similar growth, almost entirely in Europe.[22] (See Table 1–2.) Biodiesel comprises 80 percent of Europe's total biofuel production, and in 2005 the region accounted for nearly 89 percent of all biodiesel production worldwide, mainly from rapeseed and sunflower seeds.[23] Germany accounted for more than half of this production, with France and Italy generating most of the rest. The United States produced about 8 percent of the world biodiesel, mainly from soybeans.

The rapidly changing character of worldwide biofuel-production capabilities is illustrated by recent trends in the United States. In 1995, U.S. biodiesel production was 1.9 million liters (500,000 gallons); by 2004, it had jumped to 95 million liters (25 million gallons), and by 2005 it had again tripled, to more than 280 million liters (75 million gallons).[24] Current U.S. biodiesel production capacity is close to 1.2 billion liters per year (about 12 times the current output level) from 42 facilities, and more than 400 million liters per year of additional production capacity are under construction at 21 new plants.[*25] The European Union is home to approximately 40 biodiesel plants, and this capacity is also growing rapidly, both in Germany, which has been the clear leader in world biodiesel production, and also in Austria, the Czech Republic, France, Germany, Italy, and Sweden.

[*] The apparent imbalance in U.S. production capacity versus actual output is due to several factors; in some cases, rated capacity exceeds the intended output, while in other cases developers have built extra capacity in anticipation of increased demand for biodiesel fuel.

Table 1–2. World Biodiesel Production, 2005

Country or Region	Production (million liters)	Share of Total (percent)
Germany	1,921	54.5
France	511	14.5
Italy	227	6.4
Austria	83	2.4
Denmark	80	2.3
United Kingdom	74	2.1
Czech Republic	68	1.9
Poland	68	1.9
Spain	57	1.6
Sweden	9	0.3
Other Europe	23	0.6
Europe Total	3,121	88.6
United States	290	8.2
Other	114	3.2
World Total	**3,524**	**100.0**

Source: See Endnote 22 for this chapter.

1.4 World Petroleum Use and Implications for Biofuels

The doubling of petroleum prices, from about $30 per barrel in early 2004 to about $60 per barrel at the end of 2005 and subsequent price increases in 2006, has substantially heightened worldwide interest and investment in biofuels.[26] The expected growth in global demand for liquid fuels, together with increasing geological limitations in the supply of oil, has led many to assume that oil prices will remain high in years to come; in 2006 the U.S. Energy Information Administration, for instance, upgraded its forecasted price for a barrel of oil in 2025 to $54, from the previous year's projection of $33.[27]

Substantial growth in energy use in many developing countries has also begun, most notably in China and India, whose populations are by far the world's largest. From 2002 to 2004, world oil demand increased by 5.3 percent, while China's demand alone increased by a staggering 26.4 percent; demand in other Asian countries increased by 5.8 percent combined. This growth has come as oil consumption in many industrialized countries continues to rise. From 2002–04, the demand for oil increased by 4.9 percent in the United States, 10.2 percent in Canada, and 6.3 percent in the United Kingdom (demand in Germany and Japan, meanwhile, dropped by 1 percent and 2.6 percent respectively).28

While there are dramatic differences in per capita gasoline and diesel fuel consumption between industrialized and developing countries, economic growth and lifestyle changes in populous countries like China and India will likely put tremendous pressure on world petroleum supplies in the coming decades. Currently, U.S. per capita gasoline consumption is a staggering 180-fold higher than in India and 45-fold higher than in China, and U.S. per capita diesel consumption is 17-fold higher than in India and about 11-fold higher than in China. (Even German per capita consumption of these fuels is dramatically higher than in developing countries—for gasoline, about 45-fold higher than in India and 11-fold higher than in China, and for diesel, about 19-fold higher than in India and12-fold higher than in China.) However, if all the residents of China were to consume oil at the same per capita rate as people in the United States, they would require an amount greater than the current total production of oil worldwide.[29] (For national-level information on per capita gasoline and diesel fuel consumption, see Appendix A–1.)

Although per capita energy consumption in the developing world is currently low, as these countries experience economic growth and increased demand for oil, they will require new energy supplies to meet their transportation needs. For countries that depend on imported petroleum fuels, there is a clear need for alternative transport fuel supplies, either domestically produced or imported. There is an opportunity for biofuels to play an important role, particularly as petroleum costs continue to rise and as the unpredictability of future oil availability triggers national security concerns. (For national-level information on biofuel production in relation to petroleum consumption, production, and imports, see Appendix A–2; for a comparison of biofuel production as a percent of petroleum use see Appendix A–3.)

1.5 Recent Developments in the Biofuel Industry

The recent proliferation of biofuel programs around the world can be attributed to a combination of factors. Countries that wish seek to bolster their agricultural industries (long the main driver of biofuel programs) have been joined by an increasing number of nations that are concerned about such factors as high oil prices, political instability in oil-exporting countries, climate-altering greenhouse gas emissions, and urban air pollution. Continuing developments in biorefining technology have also brought greater attention to biofuels as a potentially large-scale and environmentally sustainable fuel.

A diverse range of countries around the world has recently sought new ways to promote use of biofuels. For example:

- In *Japan*, the government has permitted low-level ethanol blends in preparation for a possible blending mandate, with the long-term intention of replacing 20 percent of the nation's oil demand with biofuels or gas-to-liquid (GTL) fuels by 2030.

- In *Canada*, the government wants 45 percent of the country's gasoline consumption to contain 10 percent ethanol by 2010. Ontario will be the center of the ethanol program, where the government expects all fuel to be a 5 percent blend of ethanol by 2007.[30]

- A European Union directive, prompted by the desire for greater energy security as well as the requirements of the Kyoto Protocol, has set the goal of obtaining 5.75 percent of transportation fuel needs from biofuels by 2010 in all member states. In February 2006, the EU adopted an ambitious Strategy for Biofuels with a range of potential market-based, legislative, and research measures to increase the production and use of biofuels. Germany and France, in particular, have announced plans to rapidly expand both ethanol and biodiesel production, with the aim of reaching the EU targets before the deadline.[31]

- In the United States, high oil prices and agricultural lobbying prompted the recently enacted Renewable Fuels Standard (RFS), which will require the use of 28.4 billion liters (7.5 billion gallons) of biofuels for transportation in the country by 2012. Many U.S. government fleet vehicles that run on diesel fuel are now required to use B20 blends under new guidelines implementing the Energy Policy Act of 1992. Many in the industry believe that these targets represent a floor, rather than a limit, to biofuel production.[32]

- In Brazil, the government hopes to build on the success of the Proálcool ethanol program by expanding the production of biodiesel. All diesel fuel must contain 2 percent biodiesel by 2008, increasing to 5 percent by 2013, and the government hopes to ensure that poor farmers in the north and northeast receive much of the economic benefits of biodiesel production.

- Elsewhere in Latin America, as of 2006, *Columbia* will be mandating the use of 10 percent ethanol in all gasoline sold in cities with populations over 500,000. In *Venezuela*, the state oil company is supporting the construction of 15 sugar cane distilleries over the next five years, as the government phases in a national E10 blending mandate. In *Bolivia*, 15 distilleries are being constructed, and the government is considering authorizing blends of E25. *Costa Rica* and *Guatemal*a are also in the trial stages for expanding production of sugar cane fuel ethanol.[33] *Argentina*, *Mexico*, *Paraguay*, and *Peru* are all considering new biofuel programs as well.[34] As the world's leader in fuel ethanol, Brazil has helped many of these countries learn from its example.[35] (See Sidebar 1–1.)

- In Southeast Asia, *Thailand*, eager to reduce the cost of oil imports while supporting domestic sugar and cassava growers, has mandated an ambitious 10 percent ethanol mix in gasoline starting in 2007.[36] For similar reasons, the *Philippines* will soon mandate 2 percent biodiesel to support coconut growers, and 5 percent ethanol, likely beginning in 2007.[37] In *Malaysia* and *Indonesia*, the palm oil industries plan to supply an increasing proportion of the countries' diesel.

- Chinese and Indian planners have also sought to expand the national supply of ethanol and biodiesel. In *India*, a rejuvenated sugar ethanol program calls for E5 blends throughout most of the country, a level the government plans eventually to raise to E10 and then E20. In *China*, the government is making E10 blends mandatory in five provinces that account for 16 percent of the nation's passenger cars.[38]

- In Africa, efforts to expand biofuels production and use are being initiated or are underway in numerous countries, including Kenya, Malawi, Zimbabwe, Ghana, Ethiopia, Benin, Mozambique, Senegal, Guinea Bissau, Ethiopia, Nigeria, and South Africa.[39]

For more detailed information on international policies and initiatives underway to foster biofuel development, see Chapter 17.

Along with the rapid increase in government-supported biofuel programs, recent advances in technology have brought new interest in biofuels. In addition to producing ethanol from so-called "cellulosic" feedstock, technologies are currently being developed that will be able to convert abundant cellulosic biomass supplies to a variety of potential diesel fuel or gasoline substitutes. (See Chapters 4 and 5.)

Sidebar 1–1. Brazil's Ethanol Experience

In response to the oil crises of the 1970s, the Brazilian government turned to one of the country's oldest industries: sugar cane. By making it a national priority to build distilleries that ferment sugar into ethanol, and requiring that this fuel be mixed into all gasoline, Brazil became a global leader in the transition away from oil.

In the 1990s, rising sugar prices in Brazil coincided with lower petroleum prices, causing a drop in ethanol production and subsequent shortages. This forced the country to import ethanol and imperiled the national ethanol program, Proálcool. Several key government initiatives and market changes worked in tandem to turn this situation around. Brazil phased out sugar and ethanol quotas, as well as a constrained government subsidy program that had limited new capacity investments. It worked with farmers to help reduce sugar cane production costs and improve yields, mandated use of ethanol in government vehicle fleets, and fostered sales and use of flexible-fuel vehicles—in addition to requiring 20–25 percent ethanol blends in all regular gasoline sales.

Along with these changes, Brazil's industry has reduced ethanol production costs in a variety of ways, particularly through the increased use of sugar cane processing residues (bagasse) as fuel to produce the steam and electricity needed to process cane. The industry is also recycling organic-rich liquid effluent from cane processing (vinasse) and using it as a fertilizer and irrigation supply for cane production, thereby increasing cane yields and reducing feedstock costs. In addition, rising petroleum prices have increased the market value of ethanol. The end result is that Brazil has become the world's largest exporter of ethanol fuel while also meeting a growing share of its domestic fuel needs.

In June 2005, Brazilians could purchase ethanol for half the price of gasoline per liter (or about 75 percent as much as gasoline costs per Btu, after adjusting for the lower energy content of ethanol per liter compared to gasoline). When they do, they are not sending money to oil producers overseas, but to Brazilians. Since the 1970s, Brazil has saved almost $50 billion in imported oil—nearly 10 times the national investment through subsidies—while creating as many as 1 million rural jobs.

Source: See Endnote 36 for this chapter.

For example, a conversion system that uses high temperatures and low-oxygen conditions to convert solid biomass into combustible gases can be coupled to a gas-to-liquids (GTL) conversion process to produce liquid fuel. The "Fischer-Tropsch" (F-T) process, a technology originally developed by German researchers in the 1920s, uses chemical reactions with catalysts to convert the combustible gases from a biomass gasifier into a liquid fuel that can substitute for diesel fuel. Researchers from DaimlerChrysler, Volkwagen, and Shell have collaborated recently to develop a marketable version of this technology.[40]

In Canada and the United States, the governments have supported groundbreaking research into enzymes that could refine abundant, low-value plant fibers into ethanol. The enzyme company Novozymes, with funding from the U.S. National Renewable Energy Labratory, announced in 2005 that it could reduce the cost of some of these enzymes by 10–30 times and promised further reductions in the near future. Abengoa, a multinational ethanol company, has already begun building a facility in Spain that will utilize these enzymes.[41] In Canada, Iogen Corporation operates a pilot plant to convert straw into ethanol using enzymatic technology, and has now teamed-up with Shell, Volkswagen, and DaimlerChrysler to build a pre-commercial straw-to-ethanol plant in Europe.

Chapter 2. Liquid Biofuels—A Primer

2.1 Introduction

In order to better understand biofuel markets and the prospects for expanded biofuel use, it is helpful to examine some of the basic characteristics of these various fuel alternatives. This chapter explores the main biofuel options on the market today, including ethanol (produced from sugars and starches), ethyl tertiary butyl ether (ETBE), and lipid-derived biofuels (straight vegetable oil and biodiesel). It discusses the various fuel blends and compares the production costs of different biofuel options**.**

2.2 Carbohydrate-derived Biofuels

2.2.1 Ethanol Produced from Sugars

A variety of common sugar crops can be used as the feedstock for producing ethanol fuel, including sugar cane stalks, sugar beet tubers, and sweet sorghum stalks—all of which contain a large proportion of simple sugars. Once these sugars have been extracted they can be fermented easily into ethanol. Starch crops such as corn, wheat, and cassava can also be hydrolyzed into sugar, which can then be fermented into ethanol.

Left alone in low-oxygen conditions, the sugar in plants naturally ferments into acids and alcohols (particularly ethanol) over time; however, people have used yeast for thousands of years to expedite this process. Ethanol production starts by grinding up the feedstock so it is more easily and quickly processed. Once ground up, the sugar is either dissolved out of the material, or the starch is converted into sugar. The sugar is then fed to yeast in a closed, anaerobic chamber. The yeast secretes enzymes that digest the sugar ($C_6H_{12}O_6$), yielding several products, including lactic acid, hydrogen, carbon dioxide (CO_2), and ethanol (C_2H_5OH).[1]

Brazilian facilities are the most significant producers of sugar-based fuel ethanol in the world. The fermentation units are usually integrated into existing sugar mills, where the co-products of refining sugar cane include various grades of sugar, molasses, CO_2, and the fibrous residue of crushed sugar cane stalks, called bagasse. In Brazil, the bagasse residue is typically used as a boiler fuel to produce steam, which is used to provide process heat and often to generate electricity for use in the ethanol production process (in many cases, the excess electricity is sold to the electric grid).[2]

Even after thousands of years of development, the process of fermentation has become much more efficient in recent decades. In particular, the discovery in the 1960s of “continuous fermentation,” which permits the recycling of yeast, was a revolutionary step, substantially increasing the speed of the process and reducing the costs of heating and cooling required in single batch processing.[3] Fermentation facilities in the United States and Europe have tended to use this continuous fermentation process, while many in Brazil are only now beginning to adopt it.[4]

2.2.2 Ethanol Produced from Starches

Producing ethanol from feedstock containing large amounts of starch (such as corn, wheat, and cassava) adds an extra step to the process. Starches—polymers that are often thousands of sugar molecules long—must first be catalyzed into simple sugars. This stage, called saccharification, requires additional energy and adds to the cost of ethanol production.

The two common methods for refining starches into sugars differ primarily in the pre-treatment of the feedstock. The "wet-milling" process soaks grains in water, usually with a sulfurous acid, to separate the starch-rich endosperm from the high-protein germ and high-fiber husks. These wet mills tend to be larger and produce a number of co-products in addition to ethanol. By comparison, the "dry-milling" process involves simply grinding the unprocessed, heterogeneous seed into granules. These mills require less investment, but produce fewer co-products.[5]

The co-products of milling processes have been key to their viability. Wet mills co-produce corn oil, gluten feed, germ meal, starches, dextrin, and sweeteners such as high fructose corn syrup. Sold mostly as processed foods and feeds, these products together comprise more than one-quarter of a wet mill's economic output.[6] The primary co-product of dry mills is "dried distillers grains" (DDG), a fibrous, high-protein residue (28 percent protein) that feedlots buy as food for animals that can digest high proportions of fiber, primarily cattle. DDG can provide about 20 percent of a dry mill's income. Both wet and dry mills sometimes also sell the CO_2 released during fermentation, often to the carbonated beverage industry.[7]

Virtually all of the new starch ethanol facilities being built or expanded in the United States are dry-milling operations, since these are less costly and complex to develop than wet mills. But wet mills offer more flexibility and diversity. Wet milling facilities have the ability to switch between the production of ethanol and the production of corn syrup and/or fructose, similar in a general way to sugar cane factories, which can switch between the production of ethanol and refined sugar, depending on the markets for ethanol versus sweeteners. Because they produce a variety of products, wet mills more closely represent the "biorefineries" that may play an important role in the future.[8] (For more on biorefineries, see Chapter 4.)

2.2.3 Distilling Fuel Ethanol

Unlike ethanol produced for beverages, fuel ethanol must be distilled to have only a very small amount of water content. After removing the yeast and byproducts, ethanol distillers dehydrate the 5–12 percent solution of ethanol into a concentrated product of 95–99.8 percent ethanol.

The allowable water remaining in ethanol fuel depends on the specifications for particular end uses. Ethanol that is blended with gasoline needs to be dehydrated to have only trace amounts of water (less than about 1 percent), because water can cause problems with the fuel. Unblended "neat" ethanol, used in warm climates, can contain small amounts of water, since winter freezing conditions do not occur. For instance, neat ethanol fuel sold in Brazil contains about 4 percent water.

2.2.4 Ethanol As a Fuel

The chemical equation for a molecule of ethanol is C_2H_5OH. It can blend with gasoline, which contains a variety of larger molecules ranging from C_5H_{12} to $C_{12}H_{26}$.

A liter of ethanol contains about two-thirds as much energy as a liter of gasoline. However, pure ethanol has a high octane value, which improves the performance of gasoline by reducing the likelihood that engine knock problems will occur (engine knock occurs when the fuel combusts too soon in an engine cylinder when a vehicle is working hard to accelerate, go up a hill, or pull a heavy trailer; if the fuel ignites too soon, the combustion is not efficient in moving the vehicle forward). Adding ethanol to gasoline increases its octane level.

Since ethanol molecules contain oxygen (unlike gasoline molecules) ethanol fuel is referred to as an "oxygenate." The oxygen in ethanol can improve the fuel combustion process, helping to reduce the emission of pollutants such as carbon monoxide, ozone-forming unburnt hydrocarbons, and carcinogenic particulates. However, for related reasons, ethanol combustion also reacts with more atmospheric nitrogen, which can marginally increase emissions of ozone-forming nitrogen oxide (NO_x) gases. Since ethanol also contains a neglible amount of sulfur compared to petroleum, blending ethanol in gasoline helps reduce the sulfur content of the fuel, resulting in lower sulfur oxide (SO_x) emissions (which can contribute to both acid rain and cancer concerns). (For more on ethanol's emissions characteristics, see Chapter 13.)

Since the biomass used to produce ethanol is created by photosynthesis, the carbon dioxide created by the combustion of ethanol is generally just recycling carbon back to the air. The net reduction in greenhouse gases related to ethanol's displacement of petroleum fuel can vary substantially depending on the amount of fossil fuel used in the ethanol fuel production process. (For further discussion of biofuel climate impacts, see Chapter 11.)

Ethanol has solvent characteristics that, in high-concentration blends in particular, can cause corrosion of certain types of metal or deterioration of some rubber or plastics used in hoses and gaskets. In general, vehicle manufacturers have been able to readily use engine and fuel handling components that avoid concerns related to these solvent characteristics for ethanol blends at low levels. Another concern with ethanol is its potential to separate from gasoline under certain conditions; in cooler climates in particular, water contamination can trigger a "phase separation" of ethanol and gasoline. And blending even small amounts of ethanol with gasoline raises the fuel's vapor pressure, which can affect engine performance and contribute to ozone emissions. (For further discussion, see Chapters 13 and 15.)

2.2.5 Ethyl tertiary butyl ether (ETBE)

Due to potential concerns in blending ethanol with gasoline, one approach that oil refiners can take is to combine ethanol with isobutylene to produce an additive called ethyl tertiary butyl ether (ETBE).[9] A typical 15 percent blend of ETBE with gasoline has a biofuel content of about 6.3 percent by volume. The isobutylene component of ETBE comes from fossil fuels and thus reduces ethanol's displacement of gasoline.

ETBE has virtually the same chemical properties as methyl tertiary-butyl ether (MTBE), an oxygenate derived entirely from fossil fuels. Both are toxic and possibly carcinogenic. But ETBE differs in that it is less water soluble than MTBE. Thus while spills have led to surprisingly high concentrations of MTBE in groundwater, ETBE may disperse less rapidly and be easier to clean up. However, ETBE, like ethanol, has historically been more expensive than MTBE.[10]

ETBE has an advantage over ethanol in that it does not raise the fuel vapor pressure of gasoline blends. It also blends more completely with gasoline and will not separate if exposed to water in pipelines, ships, or trucks. Partly as a result, petroleum companies in many European countries have more readily embraced ETBE use since it is easier to manage fuel vapor pressure specifications, and it is less complicated to transport blends of ETBE and gasoline.

2.2.6 Ethanol in Fuel Blends

In most countries, ethanol has been introduced to markets as a straight blend with gasoline. Rather than manufacturing ETBE, refiners often modify the "base" gasoline to have a lower vapor pressure to accommodate the increase in vapor pressure caused by adding ethanol. In order to minimize the potential for phase separation during storage or transport, ethanol is typically "splash blended" (without stirring) in the tanker trucks that deliver gasoline to vehicle refueling stations.

Most major automobile manufacturers warranty their cars to run on ethanol blends of up to 10 percent; however, current European standards allow only for blends of up to 5 percent ethanol, although countries may prefer blends of ETBE. Sweden is the primary country in Europe that uses 5 percent blends of ethanol in gasoline, but Spain too has allowed some marketing of E5 blends, while France and Spain primarily use ETBE blends. About 30 percent of all gasoline sold in the United States is E10 (10 percent ethanol). All gasoline sold in Brazil contains 20–25 percent ethanol, a level achievable because automakers use components that are resistant to the solvent characteristics of ethanol.

Cars with specially designed engines are able to run on even higher proportions of ethanol fuel. In Brazil, ethanol-only vehicles run on "neat," hydrous ethanol, which is available at more than 90 percent of gas stations. In Brazil, the United States, and Europe, flexible-fuel vehicles (FFVs) that can run on low- and high-level ethanol blends are an increasingly popular option. In colder climates, where the low vapor pressure of pure ethanol can cause cold start problems, neat ethanol is not considered viable. Instead a blend of E85 is available for FFVs in the United States (at less than 1 percent of gas stations) and Sweden. In the winter months, the proportion of ethanol in the United States is actually adjusted to E70, again to avoid cold-start problems.

A few companies have developed additives that allow for blending 5–15 percent ethanol in diesel fuel. The preferred path to make the blend has been the use of an additive package that may contain a surfactant (to make the emulsion possible and stable), a lubricant (to compensate for the lubricity loss), and a cetane enhancer (to compensate for reductions in cetane, a measure of fuel compressibility). These ethanol/diesel blends (sometimes referred to as E-diesel) are likely to be limited to niche applications for fleet vehicles, due to technical and safety constraints associated with the relatively high volatility of ethanol/diesel blends.

2.3 Lipid-derived Biofuels

2.3.1 Straight Vegetable Oil

Straight vegetable oil (SVO) can be extracted from nearly any oilseed crop, such as rapeseed, sunflower, soybean, and palm, for potential use as a fuel in diesel engines. Used cooking oil from restaurants and animal fat from meat slaughterhouses are also potential feedstock for use in diesel fuel applications. After filtering out particles and removing water, this purified biomass-derived oil can burn directly in some internal combustion engines as well. (See Chapter 15)

Oils are usually extracted from plant seeds by first cutting them into flakes and then immersing them in a chemical solvent. (Hydraulic crushing processes have typically proven too energy intensive.) The non-oil components of the seed are often sold as a high-protein meal for animal feed, or used as a fertilizer.[11]

Due to differences in the properties of SVO compared to diesel fuel (primarily its high viscosity, especially at cooler temperatures), "neat" SVO cannot be used in normal diesel engines. In order to run on SVO, these engines must either be refitted (often by attaching a mechanism for pre-heating the oil), or they must be dedicated engines such as the *Elsbett* engine. Vehicle manufacturers generally will not warranty their engines for operation with SVO. Moreover, development of modern engines has lead in the direction of increased electronic engine and combustion control systems, which are generally not compatible with operation using SVO.[12] (See Chapter 15.)

Largely because SVO tends to gum up at colder temperatures, it has been difficult to blend it with conventional diesel fuel.[13] However, different types of plant oil have different properties that affect engine performance. Some tropical oils with more saturated, shorter-chained fatty acids, such as coconut oil, can be blended directly with diesel fuel, offering the potential for the use of SVO-diesel blends in unmodified engines in tropical locations. (See Chapter 3.)

Where saturated tropical oils are more readily available, and where warm temperatures prevent the oil from thickening, SVO may be a viable fuel. In temperate counties, technical barriers generally limit the use of SVO to niche markets. However, fuel quality standards have been defined for pure rapeseed oil in Europe, and there has been some experience with the use and handling of the fuel in daily operation. For example, efforts are currently under way in Ireland to evaluate the ability to use low-level blends of certain pure vegetable oil types in existing vehicles.[14] And the Vereinigte Werkstätten für Pflanzenöltechnologie company (VWP) has offered an enhanced service offer for SVO use focused on filter exchange and maintenance.[15]

2.3.2 Biodiesel

Compared to SVO, biodiesel is a more blendable form of lipid-based biofuel. Biodiesel is made by chemically combining the oil with an alcohol (such as methanol or ethanol) in a process known as transesterification. The resulting biodiesel is an alkyl ester of fatty acid, which contains an alcohol group attached to a single hydrocarbon chain comparable in length to that of diesel ($C_{10}H_{22}$ to $C_{15}H_{32}$).[16]

This reaction can happen by heating a mixture of 80–90 percent oil, 10–20 percent methanol, and a catalyst.[17] The catalyst is usually an acid or a base, but bases such as NaOH and KOH are the most common, in part because, with them, transesterification can happen at a lower temperature. Typical processes produce a volume of biodiesel equivalent to the volume of the original plant oil.[18]

Methanol has been the most commonly used alcohol in the commercial production of biodiesel, in part because it has typically been less expensive than ethanol. But there are also technical concerns in using ethanol, such as greater difficulties in separating the glycerin byproduct from the biodiesel, as well as a propensity for higher process energy costs.

Glycerin molecules ($C_3H_8O_3$) are the primary co-product of biodiesel production. Even though glycerin offsets only about 5 percent of the cost of producing biodiesel, it is valuable to the cosmetics, ink, lubrication, and preservative industries, and is particularly noted as an ingredient in soap.[19] The "meal" left in the seed after oil has been removed is currently sold as an animal feed.[20]

Due to the wide variety of oils and fats that can be used to produce biodiesel, there is a greater range in the characteristics of biodiesel fuels than for ethanol fuel (ethanol is actually one very specific molecule, whereas biodiesel is a mix of molecules that varies somewhat, depending on the initial oil or fat source used to produce the fuel). Some oils are shorter or more saturated—characteristics that affect the viscosity and combustibility of the biodiesel.

Rapeseed oil is the dominant feedstock used to make biodiesel in Europe, with some sunflower oil also used. In the United States, biodiesel has generally been made from soybean oil because more of this is produced domestically than all other sources of fats and oils combined. In tropical and sub-tropical countries, numerous plant oils are candidates for biodiesel production, including palm oil, coconut oil, and jatropha oil.

Biodiesel contains 88–95 percent as much energy as diesel fuel. But biodiesel can also improve diesel lubricity and raise the cetane value; thus, the fuel economy of biodiesel approaches that of diesel. Moreover, the alcohol component of biodiesel contains oxygen, which helps to complete the combustion of the fuel, reducing air pollutants such as particulates, carbon monoxide, and hydrocarbons. Like ethanol, biodiesel contains practically no sulfur, so it can help reduce emissions of sulfur oxides. (See Chapter 13.)

Biodiesel blends are sensitive to cold weather and may require special anti-freezing precautions, similar to those taken with standard number-2 diesel. Long-term storage of biodiesel can be a concern because it may oxidize, although additives can ensure stability. Biodiesel acts like a detergent additive, loosening and dissolving sediments in storage tanks and also causing rubber and other components to fail; these concerns are typically minimal at low-level blends of biodiesel, and at higher blend levels problems can be avoided with some attention to the materials used in engine fuel injectors and the overall fuel handling system. (See Chapter 15.)

2.3.3 Biodiesel As a Blend

Although conventional diesel engines operate readily with up to 100 percent biodiesel fuel, using blends above 20 percent may require modest costs to replace some rubber hoses that are sensitive to the solvent character of biodiesel. In the United States, blends of 20 percent biodiesel (B20) have been used extensively in vehicle fleets. European fuel standards permit 5 percent biodiesel blended with diesel, and blends of 2 percent biodiesel (B2) have been used with diesel fuel in numerous countries around the world.

2.4 Production Costs for Biofuels

Over the last century, biofuels have almost always been more expensive than petroleum fuels. Government incentive programs have generally been necessary to allow biofuels to play a role in the marketplace.

Adjusting for the difference in energy content, the price of ethanol produced from sugar cane in Brazil is competitive with gasoline when crude oil prices rise above the €30 ($35) per barrel range, while ethanol produced from corn in the United States is competitive when crude oil prices exceed roughly €45 ($55) per barrel. EU-produced biodiesel is competitive with oil prices at about €75 ($90) per barrel, while EU-produced ethanol becomes competitive between about €60 and €80 ($75 to $100) per barrel.[21] Outside of Europe, disparities in fuel prices between biodiesel and diesel have been greater than for ethanol and gasoline. This is primarily because plant oils grown in temperate regions are more expensive to produce than sugar or starch crops, since they are less productive per hectare of cropland. Another contributing factor is that in most countries, diesel fuel is less expensive per liter than gasoline.

Despite being generally more expensive than gasoline, biofuels have often appeared cheaper at the pump. This is in part because they contain less energy than petroleum fuels, but it is primarily because of government tax credits. In Germany, biodiesel has been 15–20 euro cents (18–24 U.S. cents) cheaper than conventional diesel, thanks to an exemption from the 47 euro cent (59 U.S. cent) tax on diesel.[22] In the United States, E85 ethanol has often been cheaper than gasoline, thanks to an 11 euro cent (13 U.S. cent) per liter excise tax credit for ethanol. These tax credits apply only to the biofuel portion of the fuel. Table 2–1 illustrates the difference in the price of gasoline and diesel with and without taxes, compared to the estimated production costs for ethanol and biodiesel in the United States, the European Union, and Brazil.[23]

Table 2–1. Production Costs of Ethanol and Biodiesel, and Prices of Petroleum-Based Fuel, in Major Biofuel-Producing Countries, 2004

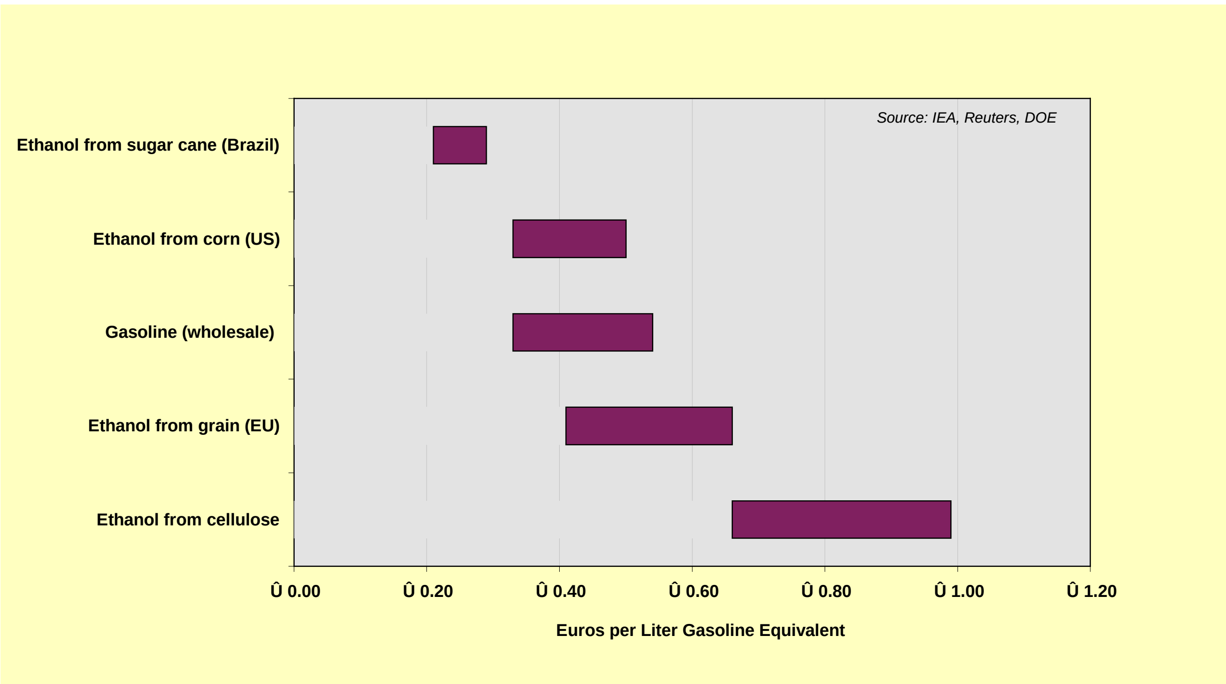
	Ethanol	Gasoline	Biodiesel	Diesel
	(Euros per energy-equivalent liter[a])			
United States	0.36 (corn)	0.45 (with tax) 0.32 (without tax)	0.50 (soy)	0.47 (with tax) 0.31 (without tax)
European Union	0.70 (wheat)	1.09 (with tax) 0.34 (without tax	0.56 (rapeseed)	1.06 (with tax) 0.33 (without tax)
Brazil	0.27 (sugar cane)	0.69 (with tax) 0.33 (without tax)	0.52 (soy)	0.40 (with tax) 0.32 (without tax)

Note: (a) Biofuel prices are accommodated for difference in energy content. Ethanol is assumed to contain 0.67 the energy of a liter of gasoline, and biodiesel is assumed to contain 0.9 the energy of a liter of diesel.
Source: See Endnote 23 for this chapter.

Feedstock costs account for the majority of a biofuel's eventual price, while processing costs and a small proportion for transport represent most of the rest. For ethanol, feedstock comprises 50–70 percent of the production cost, while for biodiesel, which requires less extensive processing, feedstock can be 70–80 percent of the production cost.[24]

Biofuels produced in more fertile tropical countries are typically less expensive than biofuels produced in more temperate regions. Yields are higher, while land and labor costs are also typically lower in tropical countries. Figures 2–1 and 2–2 illustrate the current cost ranges for ethanol and biodiesel production (at the factory gate).[25] The cost of producing ethanol from sugar cane in Brazil, for example, is roughly half that of producing ethanol from grain or sugar beets in Europe (and cheaper than the retail price of gasoline on an energy equivalent basis throughout 2005). This highlights an opportunity for tropical countries to help meet the global demand for biofuels. Typically, however, policy makers have worked to foster domestic ethanol and imposed tariffs and trade barriers to ensure that the benefits remain within their borders. Only about 10 percent of the ethanol currently produced is traded across international borders. (See Chapter 9.)

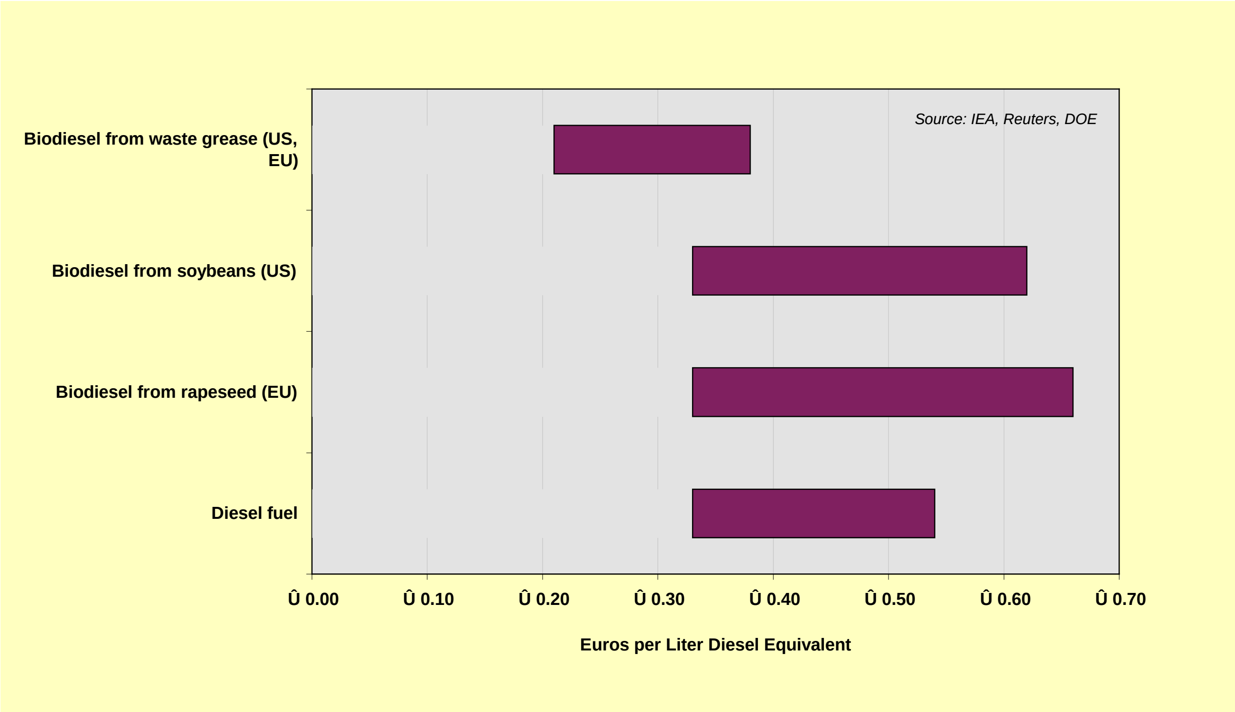
Figure 2–1. Cost Ranges for Ethanol and Gasoline Production, 2006



The value of co-products is another key to the cost of biofuels. Glycerin credits have helped to reduce the final biodiesel costs by about €4–8 euro cents (5–10 U.S. cents) per liter. The co-product credit for large dry-mill operations is in the vicinity of 2.5 euro cents (3 U.S. cents) per liter, while wet mills in the United States sell about 3.5 euro cents (4 U.S. cents) of co-products for each liter of ethanol produced.[26] However, the rapid expansion of biofuel production has saturated the market for some of these co-products, especially glycerin in Europe, undercutting their ability to reduce biofuel prices.

Conventionally produced biofuels, especially ethanol, have become significantly cheaper as the industries in Brazil and the United States have developed. In Brazil, the price of ethanol in 2005 was a third of what it was in 1980.[27] In the United States, the cost of processing ethanol declined by more than half between the 1970s and the early 2000s.[28] But still, feedstock remains the primary determinant of the cost and the primary limitation of the potential fuel supply. The variety of current feedstock is discussed in more detail in chapter 3.

Figure 2–2. Cost Ranges for Biodiesel and Diesel Production, 2006



Chapter 3. First-Generation Feedstock

3.1 Introduction

The various biomass feedstock used for producing biofuels can be grouped into two basic categories: the currently available “first-generation” feedstock, which are harvested for their sugar, starch, and oil content and can be converted into liquid fuels using conventional technology, and the “next-generation” feedstock, which are harvested for their total biomass and whose fibers can only be converted into liquid biofuels by advanced technical processes.

The focus of this chapter is on the first-generation feedstock, including sugar crops like sugar cane, sugar beets, and sweet sorghum; starch crops like corn, wheat, barley, cassava, and sorghum grain; and oilseed crops like rapeseed, soybeans, palm oil, and jatropha. The chapter also briefly addresses other oil sources for biodiesel, including sunflower, mustard seed, waste vegetable oil, microalgae, and animal oils. It concludes with a discussion of the varying production potentials for this current feedstock and its overall suitability for expanded biofuel production.

“Next-generation” feedstocks, which have much greater potential for expanding the supply of biofuels for transportation energy, are discussed in detail in Chapter 4.

3.2 Relative Feedstock Yields

In countries that have fostered the development of biofuels, the primary impetus has typically been to subsidize or otherwise support the agricultural sector. This remains a central priority to biofuel initiatives around the world, which have generally promoted agricultural crops that are already produced at a large scale for the human food and animal feed markets.

To date, only a relatively few types of crops have provided the vast majority of the world’s fuel ethanol and biodiesel. Nearly all of Brazil’s ethanol production is derived from sugar cane, currently the highest volume ethanol feedstock worldwide. In the United States, more than 90 percent of the ethanol comes from corn, the world’s second largest fuel ethanol crop and one of the most important agricultural crops globally. In Europe, about 70 percent of the biodiesel is made from rapeseed, the world’s second largest source of plant oils, with most of the remainder coming from sunflower seeds. And nearly all of the biodiesel produced in the United States comes from soybeans, the world’s largest source of plant oil (for both food and fuel uses). Interestingly, the two crops with the largest planted area worldwide—wheat (214 million hectares) and rice (148 million hectares) are not significant in biofuel production: only a modest amount of wheat is used for ethanol fuel, and no rice is used (due to higher priority demands for food markets).

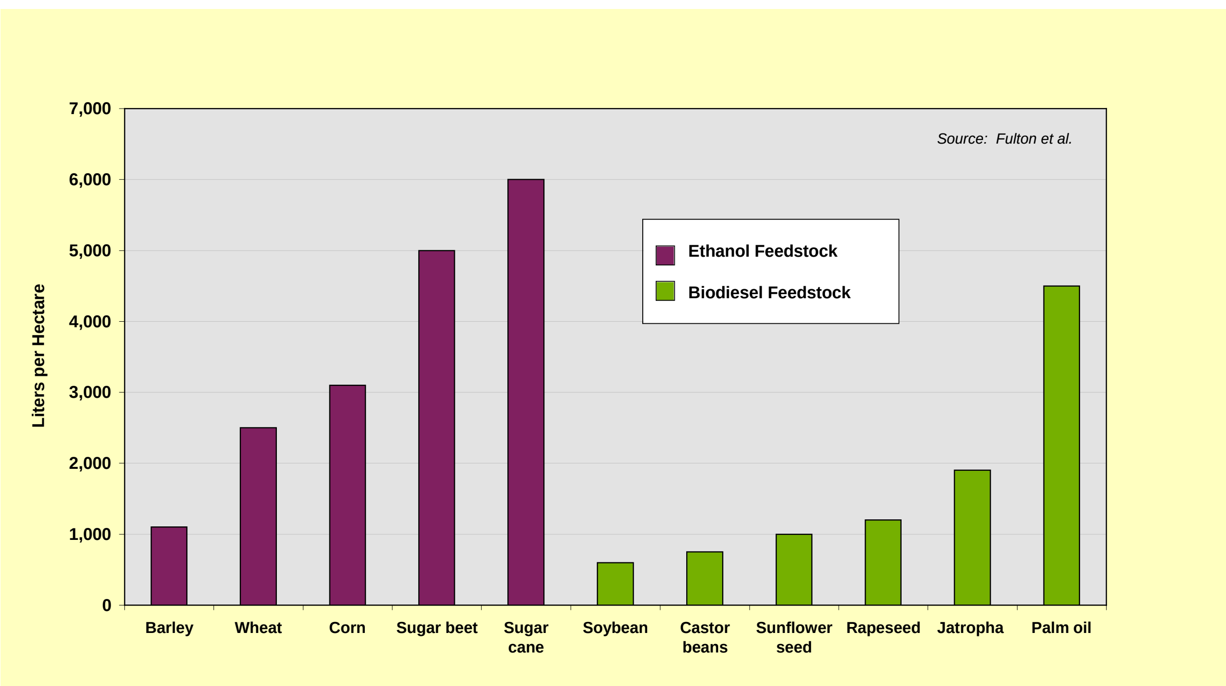
A key variable in the choice of an appropriate feedstock is the amount of biofuel that can be produced per hectare. In general, starches such as corn and wheat, which are grown predominantly in temperate regions, have lower yields than sugars such as sugar cane, which is grown in more tropical areas. In 2002, total sugar cane yields in Brazil reached 6,500 liters per hectare, more than double the corn production yield in the United States.[1] (See Table 3–1.) Likewise, oilseed crops grown in temperate areas, such as soybeans and rapeseed, have lower yields than more tropical oilseed plants, such as palm. Higher yields per hectare confer an advantage to tropical areas in the production of conventional biofuels.[2] (See Figure 3–1.)

Table 3–1. Typical Biofuel Production per Hectare of Farmland Yield, by Crop and by Region, 2002

Crop	**Typical Yield** (liters per hectare of cropland)				
Ethanol Source:	**United States**	**European Union**	**Brazil**	**India**	**Malaysia**
Sugar cane			6500	5300	
Sugar beet		5500			
Corn	3100				
Wheat		2500			
Barley		1100			
Biodiesel Source:					
Palm oil			5000		6000
Rapeseed		1200			
Sunflower seed		1000			
Soybean	500	700	400		
Jatropha				700	

Source: See Endnote 1 for this chapter.

Figure 3–1. Biofuel Yields of Selected Ethanol and Biodiesel Feedstock



3.3 Sugar Crops

3.3.1 Sugar Cane

Sugar cane is the most significant crop for producing biofuels today, supplying more than 40 percent of all fuel ethanol. The majority of the world's sugar cane comes from the center-south region of Brazil, where a long growing season, natural rainfall, and appropriate soils provide fertile conditions for cane production. On a smaller scale, ethanol is also produced from sugar cane grown in Australia, China, India, Indonesia, Pakistan, South Africa, and Thailand.

In recent years, nearly half of Brazil's annual sugar cane harvest—or 2.75 million out of 5.5 million planted hectares—has gone to producing ethanol. This represents about 0.5 percent of the country's total agricultural land area.[3] The sugar cane is produced in two distinct regions, the center-south and the north-northeast, which have very different climates, production systems, and harvesting periods. Average yields per hectare reach about 85 tonnes in the center-south, which is well suited for sugar cane, and about 70 tonnes in the north-northeast. The average sugar cane yield nationwide is 82.4 tonnes per hectare.[4]

Sugar cane stalks contain so much sugar that the plant is currently the lowest-cost source of biofuel. Cane plants produce a large amount of fiber in their stalks and leaves as well, making it possible to "co-harvest" a significant amount of cellulosic feedstock for bioenergy uses, along with the sugar harvest.[5]

Because sugar cane requires warm weather and around 850 millimeters of rainfall a year, most of the potential growing land is concentrated in the world's tropical regions, particularly in Latin America (23 percent) and Africa (18 percent).[6] Countries that export raw sugar—such as top exporters Brazil, Australia, Thailand, and Guatemala—are probably best positioned to have extra cropland capacity for sugar cane ethanol production in the near term.[7] (See Table 3–2.) Somewhat smaller sugar producers, such as Colombia, Cuba, the Philippines, and Swaziland, may begin to produce for domestic and regional markets if there is a near-term increase in ethanol demand; indeed, most of these countries are already in the process of forming significant biofuel programs.

Over the past decade, the area under sugar cane cultivation has grown at an annual average rate of 1.4 percent.[8] It is expanding the fastest in Thailand, at 2.7 percent, followed by Brazil (2.5 percent), and China and India (1.9 percent and 1.8 percent, respectively); it is interesting to note that these four countries are also the top four sugar cane producers in the world.[9] In Cuba, formerly the largest sugar supplier to the United States, the cultivated area is decreasing at an annual rate of 5.8 percent due to shortages in production equipment and fuel as well as poor primary resources and deficient technical operations for production and harvesting.[10] Brazil's center-south region contains the vast *cerrado* prairies, perhaps the largest land area in the world available for increasing agricultural acreage, and a region capable of growing highly productive sugar cane varieties. It is also a highly diverse and sensitive ecosystem. (See Chapter 12 for a discussion of environmental concerns related to sugar cane expansion.)

Table 3–2. Top 20 Sugar Cane Producers Worldwide, 2004

Country	Production	Raw Exports	Refined Exports	Total Exports
	(thousand tonnes)			
Brazil	26,400	10,820	4,420	15,240
India	15,150	0	250	250
China	10,096	10	57	67
Thailand	7,010	2,281	2,579	4,860
Mexico	5,330	7	7	14
Australia	5,178	4,017	140	4,157
Pakistan	4,023	0	214	214
United States	3,590	0	261	261
Colombia	2,680	620	580	1,200
South Africa	2,560	765	305	1,070
Cuba	2,450	1,900	0	1,900
Philippines	2,340	202	0	202
Argentina	1,925	45	156	201
Guatemala	1,850	1,125	210	1,335
Indonesia	1,730	0	0	0
Vietnam	1,250	0	100	100
Egypt	960	0	0	0
Peru	959	61	0	61
Sudan	830	55	160	215
Swaziland	628	283	2	285
Subtotal	96,939			
World	107,890			

Source: See Endnote 7 for this chapter.

3.3.2 Sugar Beets

Sugar beets are an important source of sugar in Europe, and a valuable feedstock for biofuels in France. Europe is the principal producer, where average yields vary from 53 tonnes per hectare in Germany to 58 tonnes per hectare in the Netherlands.[11] Ukraine and Russia have the largest cultivated area, but the largest producers by volume are France and Germany. Worldwide, the total area cultivated in sugar beets is decreasing by 3.5 percent a year; in Ukraine, it is shrinking by 7.4 percent annually, and in Russia, by 3.3 percent annually. France's sugar beet yield per hectare is the highest of the 10 countries with the largest cultivated area.

Sugar beets generate good yields in many temperate settings, but compared to tropical sugar cane, they are a more chemical- and energy-intensive crop.[12] Due to concerns about the potential survival of pests in the soil, the beets cannot be cultivated more than once every three years on the same field, and yields depend strongly on climatic conditions. Since the plant root must be processed to obtain the sugar, producing ethanol from sugar beets is more energy intensive and costly than producing it from cane. In general, harvesting and processing sugar beets is a heavily mechanized operation.

Since beets are a more expensive feedstock than sugar cane, their economic sustainability has often depended on government protection through subsidies and tariffs on imported sugar (in particular sugar made from cane). Recent shifts in European subsidy schemes have prompted beet growers to seek other markets for their crops, including ethanol, though some have considered switching to another crop entirely, such as wheat or rapeseed.[13] (See Chapters 9 and 19 for more on changing EU agriculture sector supports.)

3.3.3 Sweet Sorghum

Although currently not a significant ethanol feedstock, sweet sorghum deserves particular attention as a multi-use crop. Farmers can harvest the seeds at the top of the plant for food and the sugars in the stalk for fuels. In settings where land is particularly scarce, this co-harvesting of sorghum may be particularly efficient.

As with sugar cane, the sugar in sweet sorghum is found in the plant's main stalk. The crop grows particularly well in drier, warmer climates, though it can also be grown in temperate areas. With its drought tolerance and ability to produce sugar, sweet sorghum could receive increasing attention as a feedstock for ethanol production.

3.4 Starch Crops

3.4.1 Corn

Corn is the second largest source of biofuel feedstock today, primarily because of its dominance in the United States for ethanol production. Corn ethanol production is centered in several states in the U.S. corn belt, including Illinois, Iowa, Minnesota, South Dakota, and Nebraska. A much smaller amount of ethanol is produced from corn grown in northeastern China and South Africa. In the United States, 98 percent of the corn crop is treated with synthetic nitrogen fertilizers, and 97 percent of cornfields are treated with herbicides.[14]

Producing ethanol from grain starches is more land intensive than producing it from sugar cane, because corn crops have lower fuel yields per hectare. As a result, while the United States and Brazil produce comparable amounts of ethanol, the U.S. must use almost twice as much land to fuel production (about 5 million hectares vs. 2.7–3 million hectares). In comparison to sugar cane, corn starch must also undergo additional processing to convert it into sugars before it can be fermented to ethanol fuel. However, one advantage of corn as a feedstock is its longer "shelf-life" before processing; while corn can be stored for long periods after harvesting, sugarcane must be processed very quickly (usually within 24–48 hours).

3.4.2 Wheat

The global volume of ethanol fuel produced from wheat is considerably lower than the quantity produced from sugar cane and corn. In the United States, less than 3 percent (approximately 445 million liters) of the installed ethanol fuel capacity comes from wheat.[15] Spain and Germany also produce shares of domestic ethanol from wheat, both producing between 130–270 million liters annually.[16] Canada and France are smaller producers, generating 70 million liters and 58 million liters of ethanol from wheat, respectively, in 2002.[17] As with corn, only the kernel portion of the cereal (which contains the starch) is used to produce ethanol. Overall, the ethanol yield per hectare of wheat is lower than for corn and sugar crops.

Because wheat is an important food source, most of the wheat produced in the world today is consumed as human food. The total cultivated land area is increasing only slightly, showing just 0.03 percent annual growth over the last 10 years.[18] Wheat yields per hectare vary considerably depending on weather and climate factors, averaging around 5.7 tonnes in the European Union (15 countries), 3.8 tonnes in China, 2.7 tonnes in India, and 2.4 tonnes each in the United States and Russia.[19] The average wheat yield worldwide has increased by 1.7 percent annually over the last decade.

Two relatives of wheat—rye and barley—are also used for ethanol production. As crops, they are resistant to drier and cooler conditions, and can grow in more acidic soils. As feedstocks for ethanol they are significant primarily in northern Europe. Demand for rye as both a food and a feed has declined in recent years, though new ethanol plants have stimulated some additional planting.[20]

3.4.3 Cassava

Cassava, or tapioca, is the most cultivated crop in Sub-Saharan Africa. It is the second most-grown crop in Africa overall, fourth in Southeast Asia, fifth in Latin America and the Caribbean, and seventh in Asia. While more than 60 percent of the world's cassava is grown in Africa, the highest yields are achieved in Asia due to less disease, fewer pests, and relatively intensive crop management, including irrigation and fertilizers. Because of its high tolerance, cassava is typically cultivated in marginal areas with poor soils and high risk of drought.[21]

Cassava has long been considered a candidate for ethanol production, and it is beginning to be a more significant feedstock. Brazil considered ethanol production from cassava during the 1980s, but yields were lower than sugar cane, the crop was more labor intensive, and the processing was considerably more complex—and commercial production of ethanol from cassava never took off. However cassava is a highly productive crop. Thailand has begun using it on a larger scale for its ethanol program, while Nigeria has placed cassava at the center of its planned ethanol program.[22]

3.4.4 Sorghum Grain

Sorghum grain is used only to a limited extent for the production of fuel ethanol. It is a distant second to corn for ethanol production in the United States. Over the past decade, the area cultivated in sorghum worldwide has been decreasing by 0.1 percent a year; in the United States, India, and Sudan it decreased by 3 percent, 2 percent, and 1 percent, respectively.[23] However, the annual cultivated area is growing in Nigeria and Niger, by 2 percent and 1 percent respectively.

Only 4 percent of the world's sorghum production is processed into ethanol, most of which is used for non-fuel purposes. Of the remainder, 44 percent is used in animal diets, 43 percent is consumed as human food, and 7 percent becomes waste crop. The amount of crop waste generated in sorghum cultivation is 3.8 million tonnes, and could be a potential source for "next-generation" biofuel production.

3.5 Oilseed Crops

Oilseed crops provide the primary feedstock for producing biodiesel. Of the major oilseeds cultivated today, soybean production is by far the world's largest, followed by rapeseed and cottonseed.[24] (See Table 3–3.) The dominant feedstock used in biodiesel, however is rapeseed (primarily in Europe).

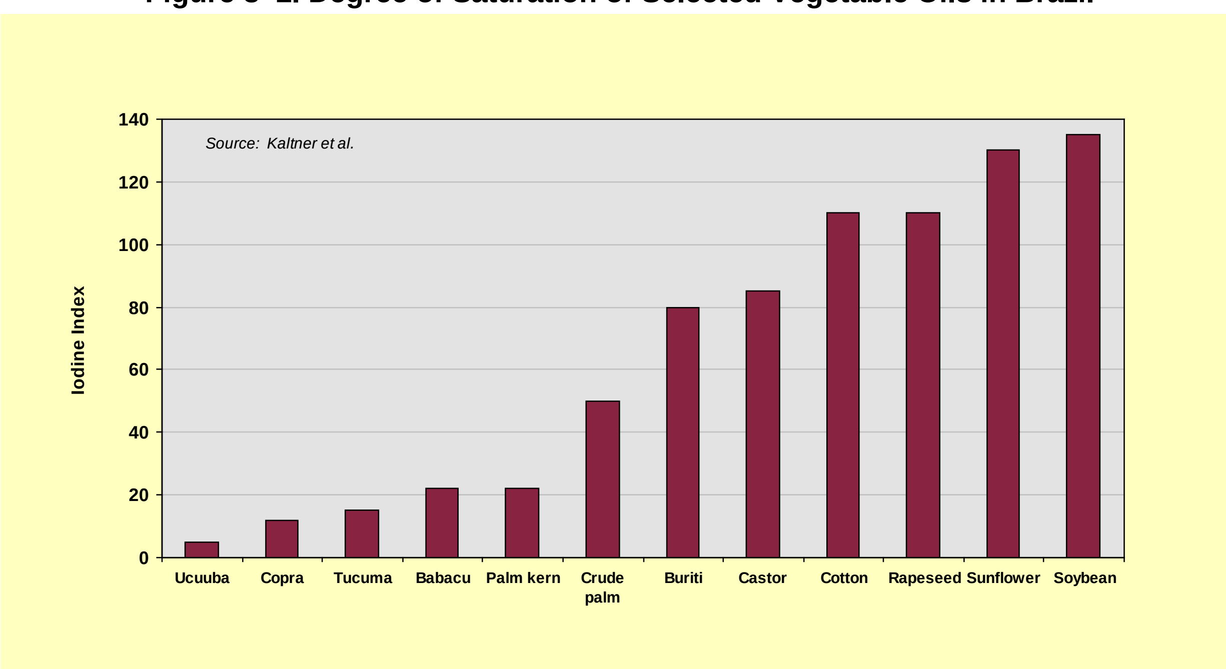
Table 3–3. World Production of Major Oil Seed Crops, 2004–2005

Crop	Production (million tons)
Soybean	215.3
Rapeseed	46.1
Cottonseed	45.2
Peanut	33.1
Sunflower seed	25.7
Palm kernel	9.5
Copra	5.4
Total	**380.3**

Source: See Endnote 24 for this chapter.

In temperate regions, oilseed crops typically generate lower yields per hectare than starchy cereal feedstock such as corn and wheat. But because oil seeds require less processing, they generally have more favorable energy balances overall. Oilseed crops grown in tropical areas can be especially productive.

Figure 3–2. Degree of Saturation of Selected Vegetable Oils in Brazil



Oilseed species vary considerably in their oil saturation and fatty acid content, characteristics that significantly affect the properties of the biodiesel produced. Highly saturated oils produce a fuel with superior oxidative stability and a higher cetane number (a measure of a diesel fuel's quickness to ignite), but which performs poorly in low temperatures. (See Chapters 2 and 15.) For this reason, vegetable oil with a high degree of saturation is more suited for use in warmer climates. Figure 3–2 above compares the degree of vegetable oil saturation for a variety of oils that could be produced in Brazil.[25] (Higher iodine numbers correspond to a greater percentage of polyunsaturated oil content.[26])

3.5.1 Rapeseed

As noted earlier, rapeseed is the primary feedstock for biodiesel production in Europe. Commonly grown in rotation with cereal crops, it is a relatively productive oil seed and accounts for the highest output of biodiesel per hectare in the EU when compared to soybeans, sunflower seed. (See Table 3–1.) Like most oil seeds grown in temperate climates, however, rapeseed yields a lower quantity of fuel per hectare than starchy crops such as wheat and sugar beet.

To avoid the spread of plant disease, at least two years should be left between the cultivation of rapeseed and other cruciferous crops, such as broccoli, cauliflower, cabbage, and brussel sprouts. This restriction, along with soil quality considerations, tends to limit the expansion opportunities for rapeseed cultivation.[27] Nonetheless, the global cultivated area is growing by 2 percent annually. In China, the world's largest rapeseed producer, the area planted is expanding rapidly, while in India, the third largest producer, growth is minimal.[28] Australia, the world's seventh largest rapeseed producer, has seen recent increases in cultivated area of 12 percent per year. In 2006, rapeseed harvest in Germany is expected to use 1.4 million hectares of land, up from 1.32 million hectares in 2005; roughly 48 percent of total rapeseed oil production in 2005 Germany was used for biodiesel production.[29]

Table 3–4. Top 10 Rapeseed Producers Worldwide, 2004

Country	**Production (thousand tonnes)**
China[a]	11,900
Canada	7,001
India[a]	6,800
Germany[b]	5,250
France	3,961
United Kingdom[a]	1,612
Australia	1,549
Poland	1,292
Czech Republic[a]	910
United States	572

Note: (a) unofficial figure; (b) FAO estimate.
Source: See Endnote 31 for this chapter.

In Europe, 1.4 million hectares of rapeseed was planted specifically for biodiesel use in 2005.[30] The continent's biodiesel producers typically have special arrangements with their governments to produce a certain amount of feedstock for biofuel production, usually on set-aside land. About half of this production was in Germany, but France, the Czech Republic, and Poland were also significant growers.[31] (See Table 3–4 above.)

3.5.2 Soybeans

Soybeans are the dominant oilseed crop cultivated worldwide, far surpassing the output of other oil crops. World production of soybeans totaled 215 million tonnes in 2004–05, accounting for 57 percent of major oilseed production. Brazil, the United States, and Argentina dominate world soybean production, accounting for an estimated 30 percent of the global supply for export.[32] Primarily because of its prevalence, rather than it specific desirability as a biofuel feedstock, soy oil is increasingly being used for biodiesel production in these countries.

Although soybeans generate a relatively low yield of biodiesel per hectare when compared to other oilseed crops, they can grow in both temperate and tropical conditions. As a nitrogen-fixing crop, they also replenish soil nitrogen and require less fertilizer input, giving them a relatively favorable fossil energy balance. (See Chapter 10.) Soybeans are grown in rotation with corn in the United States and with sugar cane in Brazil

Soybean harvesting tends to be highly mechanized and is controlled almost exclusively by large multinational agricultural processors. American companies Cargill and ADM are heavily invested in Brazil's soy industry. Of total soybean production worldwide, 86 percent is used in food manufacturing and 8 percent is consumed directly as human food or animal feed. Only a small fraction of the soybean supply is currently transformed into fuels.

3.5.3 Palm

Palm is an attractive candidate for biodiesel production because it yields a very high level of oil per hectare. The two largest producers are Malaysia and Indonesia, where palm oil production has grown rapidly over the last decade (by 4 percent and 11 percent, respectively). Nigeria has the second largest planted area, but its annual growth rate is only 1 percent due to the low yield of palm fruit per hectare.[33] Brazil currently produces only a small share of the world's palm oil, but it has the potential to significantly expand production in the north; the African palm has been identified as the most promising species for Brazilian biodiesel use.[34]

While most palm oil is used for food purposes, the demand for palm biodiesel is expected to increase rapidly, particularly in Europe. The Netherlands is the EU's largest importer of palm oil, followed by the United Kingdom. UK imports alone doubled between 1995 and 2004, to 914,000 tonnes, which represented 23 percent of the EU total.[35]

3.5.4 Jatropha

Jatropha curcas is an oilseed crop that grows well on marginal and semi-arid lands. The bushes can be harvested twice annually, are rarely browsed by livestock, and remain productive for decades. Jatropha has been identified as one of the most promising feedstock for large-scale biodiesel production in India, where nearly 64 million hectares of land is classified as wasteland or uncultivated land.[36] It is also particularly well suited for fuel use at the small-scale or village level. (See Chapter 8.)

The economic viability of biodiesel from jatropha depends largely on the seed yields. To date, there has been a substantial amount of variability in yield data for the plant, which can be attributed to differences in germplasm quality, plantation practices, and climatic conditions. In addition, due to absence of data from block plantations, several yield estimates are based on extrapolation of yields obtained from individual plants or small demonstration plots. D1 oils, a British company aiming to cultivate biodiesel in the developing world, has chosen jatropha as its primary feedstock due to the plant's high oil content, ability to tolerate a wide range of climates, and productive lifespan of as much as 30 years.[37]

Several agencies promoting jatropha are projecting significantly improved yields as the crop is developed. In India, researchers estimate that by 2012, as much as 15 billion liters of biodiesel could be produced by cultivating the crop on 11 million hectares of wastelands.[38] Further development and demonstration work is needed, however, to determine whether these levels of productivity are feasible.

3.6 Other Potential Oil Sources for Biodiesel

3.6.1 Oilseed Crops and Tree-based Oilseeds

Many other plant varieties could be promising feedstock for biodiesel production in the future. Some are already grown on a wide scale, while others are only now being evaluated for their specific characteristics, including high yields and the labor intensity of production.

Potential plant oil feedstocks currently grown or available widely include:

- *Sunflower.* The world's fifth largest oilseed crop, it accounts for most of the remaining biodiesel feedstock in Europe after rapeseed. Sunflower seed generates a higher yield of biodiesel per area when compared to soybeans, and a yield similar to rapeseed. Though slightly less productive than rapeseed, it is heartier and requires less water and fertilizer.[39]

- *Cottonseed.* The world's third largest oilseed crop, it is produced predominantly in India, the United States, and Pakistan, which are together responsible for 45 percent of world production and 50 percent of the total cultivated area.[40]

- *Peanut.* The world's fourth largest oilseed crop, it accounts for 8.7 percent of major oilseed production. The major producers are China, India, and the United States, which together account for 70 percent of world production. China and India represent 56 percent of the world's cultivated area.

- *Mustard seed.* A relative of rapeseed and canola, it provides a potentially valuable non-food feedstock. The plant's roots, stems, and leaves contain glucosinolates that break down in the soil into a variety of active but biodegradable chemicals, which provide a pesticide effect. Removal of the plant oil leaves a co-product meal—residual press cake—with a strong potential market (and environmental) value as an organic pesticide. To create a viable biodiesel feedstock, however, genetic engineering would likely need to be applied to boost the oil content of the seeds and to increase the effectiveness of the residue for pesticide use.[41]

- *Coconut.* The favored feedstock in the burgeoning biodiesel industry in the Philippines, it is another high yielding feedstock that produces a highly saturated oil. Studies have shown that vehicles running on coco-biodiesel reduce emission levels by as much as 60 percent and increase mileage by 1–2 kilometers due to increase oxygenation, even with 1 percent minimum blend.[42]

- *Castor oil*. Identified as the second most-promising species for Brazil after palm oil, the castor oil, or momona, plant is a particularly labor-intensive crop that could provide jobs in the poorer northeastern regions of the country. India is the largest producer and exporter of castor oil worldwide, followed by China and Brazil. World demand for castor oil is projected to continue growing by 3–5 percent per year in the near term.[43]

- *Waste vegetable oil.* Soybean, rape, palm, and coconut are the waste oils most frequently used in biodiesel production. Their use requires additional processing to filter out residues and to handle the acids produce by high temperatures. At present, China produces most of its biodiesel using waste oil from cooking—using between 40 and 60 thousands tons of cooking oil a year. It is estimated that Chinese biodiesel may be available on a large scale for the transportation sector by 2007 or 2008.[44]

Beyond these common plant oils, more than 100 native Brazilian species have been identified as having potential for biodiesel production, most of them palm tree species. India, too, is home to more than 300 different tree species that produce oil-bearing seeds. Given the large demand for vegetable oil for human food use worldwide, there is particular interest in identifying non-edible species that can be grown in arid to semi-arid regions poorly suited for food crops. The most promising non-edible sources are: jatropha, pongamia, melia (neem), and shorea (sal).[45]

Poorer populations have typically collected and sold tree-based oilseeds for use as a lighting fuel. The oils are also used in soaps, varnishes, lubricants, candles, and cosmetics. Non-edible oilseeds are not currently utilized on a large scale, but such oils can be an important component of local economies.[46] (See Chapter 8.)

3.6.2 Microalgae

Microalgae are microscopic single-cell aquatic plants with the potential to produce large quantities of lipids (plant oils) that are well suited for use in biodiesel production. Microalgae can be grown in arid and semi-arid regions with poor soil quality, with a per-hectare yield estimated to be many times greater than that of even tropical oil seeds. Algae can also grow in saline water, such as water from polluted aquifers or the ocean, which has few competing uses in agriculture, forestry, industry, or municipalities.[47]

Algae feedstock received early attention from the U.S. National Renewable Energy Laboratory in the 1980s, and interest in them has recently resurged based on their potential for cultivation near power plants. The primary nutrients for growing microalgae are carbon dioxide (CO_2) and nitrogen oxides (NO_x), creating an opportunity for developing integrated systems that produce oil-rich microalgae that feed on the emissions of coal, petroleum, and natural gas power plants.

Recent efforts at the Massachusetts Institute of Technology in the United States have demonstrated promising technology for using microalgae to clean up power plant emissions. A private start-up company, GreenFuel, is working to commercialize this technology. Such algae colonies could reduce NO_x levels by some 80 percent and CO_2 by 30–40 percent, while also producing a large quantity of raw algae bioenergy.[48] By selecting the right microalgae, the single-cell plants can produce 40–50 percent oil by weight.[49] However, the cost of cultivating algae in other scenarios is likely to make it uneconomical in the near term.[50]

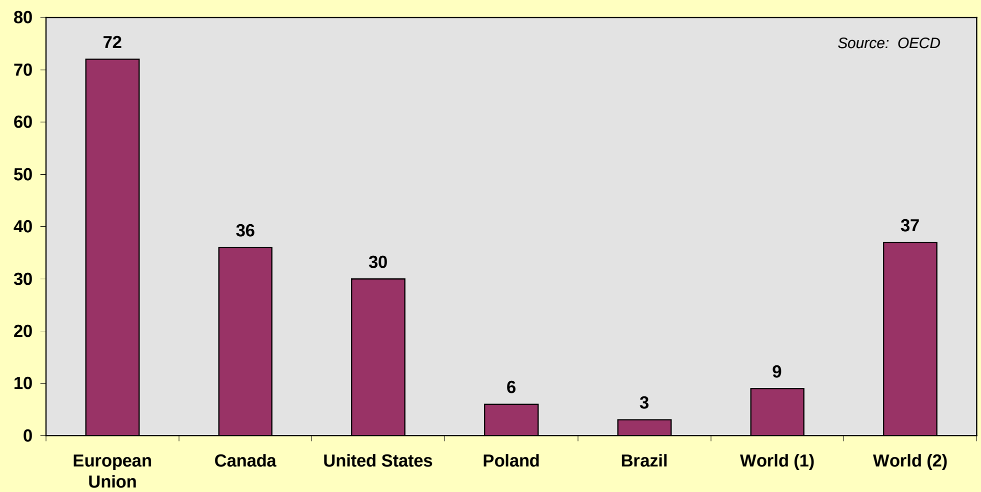
3.6.3 Animal Fats

Animal fats may be gathered from cattle or chicken processing and are increasingly being considered for the production of biodiesel, especially to replace fuel in vehicle fleets for companies producing these raw materials.[51] The low retail price of suet (animal fat) has made this raw material attractive; however, the material is not always readily available and is often restricted because it is a sub-product, and therefore has not been produced primarily for a biodiesel program. Chicken oil has similar potential to cattle oil, but has only recently become available on a large scale, and its use will be contingent upon inventory availability and greater investment in research.[52]

3.7 Potential and Limitations of Current Feedstock

The starch, sugar, and plant oil feedstock that current technologies are able to convert into ethanol and biodiesel will dominate the biofuel industry in the near term. But these inputs will ultimately be limited in comparison to cellulosic feedstock, the potential of which is covered in Part 2 of this report. Nevertheless, some current feedstock has much greater biofuel potential than others. In general, crops grown in tropical settings can produce large quantities of fuel more easily than those cultivated in temperate climates.

Figure 3–3. Percentage of Agricultural Land Required for 10% Biofuel Shares in Major Biofuel Producing Regions



Notes: World area shares are calculated relative to land used for cereals, oilseeds and sugar globally (World 1) and within the five major biofuel producing regions (World 2). All area requirements are calculated on the basis of average crop area and yield data for 2000-2004 an transport fuel consumption in 2004. For these calculations, the 2004 shares in the feedstock mix are assumed to remain unchanged.

As Figure 3–3 illustrates, the amount of land necessary to cultivate biofuel feedstock varies greatly depending on the type of feedstock and the conditions in different regions.[53] This figure primarily illustrates the difference in yields between sugar cane grown in tropical regions, versus yields for cereal and oilseed crops grown in temperate regions. It should be noted that the land area estimates in this figure do not take into account potential contributions from agricultural residues, forest residues, or perennial energy crops (which are anticipated to have much higher yields in temperate regions than cereal or oilseed crops).

3.7.1 Fuel Production Potentials of Current Feedstock

Figure 3–3 shows the proportion of cropland that would be required for countries to displace 10 percent of the transportation fuel supply with crops currently used to produce biofuels. The limitations of these crops in temperate countries are clear, while the potential opportunities for countries such as Brazil are also clear. This potential exists not only because Brazilians drive less than Americans and Europeans on average, but because tropical crops are more productive than temperate crops.

Ethanol: The Limitations of Starch and the Risks of Sugar Cane Expansion

Corn is the highest-yielding cereal feedstock used in ethanol production today. In 2005, 15 percent of the U.S. corn crop (converted into ethanol) displaced some 2–3 percent of the country's gasoline.[54] However, corn typically requires large amounts of fertilizer to achieve high yields, and processing it requires more energy than extracting sugar from cane.

As such, sugar cane has much greater potential to supply a significant portion of the world's transport fuels. According to the U.N. Food and Agriculture Organization (FAO), the total area potentially available for sugar cane, excluding forests, amounts to 153 million hectares (to put this into perspective, Brazil currently devotes about 5.5 million hectares to sugar cane production).[55] Assuming the near-best productivity now achievable, as well as efficient use of sugar cane residues for energy, one particularly optimistic study concluded that 143 million hectares of this land could produce 163.9 exajoules of primary energy per year and 90 exajoules of final energy per year in the form of liquid fuel (alcohol) and electricity.[56] This is an amount comparable to about 40 percent of the world's current primary energy consumption, and 60 percent more than current transportation energy consumption. Another study concluded that sugar cane grown in tropical areas could relatively easily produce enough fuel to displace 10 percent of global gasoline demand by 2020.[57]

The Brazilian *cerrado*, a biologically diverse area that is largely uncultivated, is by far the largest area remaining worldwide for expanding sugar cane plantations. Expansion of such cultivation would likely come at great ecological expense to the region, however. (See Chapter 12.)

Biodiesel: The Limitations of Temperate Oilseeds and the Risks of Tropical Oilseed Expansion

Although rapeseed is among the most productive oilseed crops able to grow in Europe and other temperate regions, its ability to displace diesel fuel is limited. Currently, about 20 percent of the EU rapeseed crop is used to produce just 1 percent of the diesel fuel, and analysts have predicted that rapeseed supplies will be insufficient to meet the EU biofuel target of 5.75 percent of transport fuels by 2010.[58]

Likewise, soybeans are constrained by their comparatively low yields. For instance, if the entire oil crop of the world's top 10 soybean-growing countries were converted into biodiesel, this would generate 34 billion liters of biodiesel (1.12 exajoules of energy in the form of liquid fuels)—enough to meet only about 1 percent of the current demand for transportation fuels. There is far less room to expand soybean cultivation in the United States compared to Brazil and Argentina.[59]

Higher-yielding tropical oil seeds have greater promise to use land more efficiently. The palm industries in Malaysia and Indonesia expect to ramp-up their production of palm oil significantly, and could satisfy a large proportion of Europe's future demand for biodiesel. However, as with the anticipated expansion of Brazil's sugar cane industry onto further stretches of the cerrado prairies, large palm oil plantations are displacing wilder ecosystems and have been a primary motivation for the burning of rain forests in Southeast Asia in recent years. (See Chapter 12.)

3.7.2 Prospects for Improving Crop Yields

Modern agriculture has changed considerably since the early 20th century, mainly due to mechanization, increased use of fertilizer and other inputs, and dramatically higher yields of major grain and fiber crops. These heightened yields were a direct result of agricultural research, such as corn and wheat hybridization, as well as governmental price support policies, which fostered continued investments in new equipment for cultivating and harvesting corn and wheat.

The areas with the greatest potential for improving crop yields are in the developing world, where traditional farming methods are less productive and farmers often operate on a small scale, without mechanized tools or sufficient inputs. But over the years, agriculture in industrialized countries has also become more productive, increasing the maximum achievable yields for crops as well.

In the past, agricultural yields in the European Union (EU-15) improved at an average rate of 1 percent per year, in equal parts due to genetic breeding and technical farming improvements.[60] In Germany, a 2 percent annual increase in yields was achieved from the 1950s to the present.[61] And in the United States, corn grain yields have risen steadily over the past 25 years (1975–2000), at an average annual rate of 1.2 percent, even while fertilizer inputs have declined. Similar improvements have occurred in Brazil with sugarcane and soybeans.[62] (See Table 3–5.)

Table 3–5. Yield Improvements in Selected Feedstock Crops

Crop	Location	Time Period	Average Yield or Improvement	Percent Increase
Sugar cane	Brazil	1990/91–2002/03	63 tons/hectare in 1990 to 66 t/h in 2002	5
Sugar cane	Brazil (center-south)	2005	~69 t/h	–
Corn	United States	1975–2003	86 bushels/acre to 142 bu/ac	65
Soybeans	Brazil	1940/41–2000/01	651 kg/h/year to 2,720 kg/h/yr	318
Soybeans	United States	1990–2001	31.6 bu/ac to 37.12 bu/ac	17
Oil palm	–	1960s–2000s	–	~200

Source: See Endnote 62 for this chapter.

Agriculture will continue to adapt to new technologies and circumstances, including biotechnology, which is transforming production by making available genetically altered varieties of corn, soybeans, sugar cane, and other crops. The breeding of hybrids and crops that can grow in close proximity have helped achieve higher corn yields, and genetically modified (GM) varieties offer promise to increase these yields further.[63] Biotech corn hybrids accounted for 40 percent of the total planted acreage in the United States in 2004.[64] In Brazil, yields of both soybeans and sugar cane have increased through breeding and genetic modification, as well as the increased use of pesticides and fertilizers.[65] (See Sidebar 3–1.)

Plant breeding has also played a major role in boosting the yields of oil palm, and new clonally hybrids promise even higher yields. More dramatic genetic modification of crops may bring still higher yields, while the next generation of lignocellulosic crops could be bred to maximize not food yields but raw energy content (See Chapter 4 for more on breeding next-generation feedstock.) The development of very high yield crops could be limited, however, by a lack of public acceptance for GM crops and intensified energy crop cultivation.[66] (See Chapter 12 for more on GMOs.**)**

Sidebar 3–1. Biotechnology and Enhanced Sugar Cane Production in Brazil

When Brazil launched its Proálcool program in the 1970s, average ethanol production in the country was around 2,000 liters per planted hectare, and the total planted area was about 1.5 million hectares. By 1999, however, ethanol yields had more than doubled to 5,000 liters per hectare, and by 2004 they averaged 5,900 liters per hectare. Today, yields are as high as 7,000 liters per hectare under good conditions, triple the output of 30 years ago, representing an average annual increase of 3.8 percent. Sugar cane is currently cultivated on about 5.5 million hectares, spread over the 27 states of the Brazilian Federation.

The use of biotechnology has been key to enhanced sugar cane production in Brazil. In the 1970s, only 10 different varieties of the crop were available in the country. Today, more than 550 varieties are cultivated, and the production period has increased from 150 days to 220 days. In the last decade alone, 51 new sugar cane varieties were released, the predominant 20 of which now occupy 70 percent of the total planted area. Those varieties were produced mainly through genetic improvement. The germplasm bank of Brazil’s Copersucar program contains more than 3,000 genotypes, including a large collection of native (wild) species that are the precursors for modern sugar cane varieties and the source of the great genetic variability found in the plant.

In 2003, a private Brazilian investment group, Votorantim, created the enterprise Canavialis, with a large laboratory for genetic selection and development of sugar cane. Each year, the laboratory releases more than 1.5 million seedlings to be planted and tested on three farms (called experimental stations) located in different parts of the country. The Votorantim Group also formed a biotechnology company, Alellys, dedicated to modifying the genetic composition of sugar cane varieties produced by Canavialis. New varieties that are more productive and resistant to diseases are under development.

Source: See Endnote 65 for this chapter.

3.8 Conclusion

Over the next decade, existing starch, sugar, and oilseed crop varieties will continue to provide the bulk of the biomass supplies used for biofuel production. Biofuels grown in tropical areas are cheaper and can displace a larger share of petroleum than biofuels produced with more temperate feedstocks. European countries will likely find it preferable to import biofuels rather than attempt to grow all of their own. The United States may be able to produce more indigenous biofuel, but will ultimately face similar limitations.

Sugar cane in particular stands out as a feedstock that could provide a large amount of transportation fuel, while palm oil, jatropha, sorghum, and cassava could also help displace large quantities of petroleum. However, as elaborated in Chapter 12, the expansion of such tropical feedstock, especially sugar and palm, threatens sensitive ecosystems and may not be desirable.

Although the yields of both temperate and tropical biofuel crops will probably continue to increase, they will still likely remain limited in comparison to the next generation of feedstock. Algae, which is included as a “first-generation” feedstock because it can be processed with the same conversion technologies, stands alone as a feedstock with huge theoretical, though not yet economical, potential. There is much greater and more sustainable long-term potential for biofuels produced not from the sugars, starches, and oils of plants, but from their more abundant fibers, as discussed in Chapter 4.

Continuing to increase the yields of conventional crops may thus become important mainly as a way to free up agricultural land for the production of dedicated energy crops. This potential is discussed in greater detail in Chapter 6.

PART II. NEW TECHNOLOGIES, CROPS, AND PROSPECTS

Chapter 4. Next-Generation Feedstock

4.1 Introduction

Cellulosic biomass such as wood, tall grasses, and forestry and crop residues are expected to significantly expand the quantities and types of biomass feedstock available for biofuel production in the future, as new conversion technologies are developed that enable the production of biofuels from these feedstock. Over the next 10–15 years, it is expected that lower-cost residue and waste sources of cellulosic biomass will provide the first influx of “next-generation” feedstock, with cellulosic energy crops expected to begin supplying feedstock for biofuel production toward the end of this timeframe, then expanding substantially in the years beyond.

There are a variety of reasons why cellulosic biomass is considered an attractive option. The use of waste biomass offers a way to create value for society, displacing fossil fuel with material that typically would otherwise decompose, with no additional land use required for its production. Cellulosic biomass from fast-growing perennial energy crops, such as “short-rotation” woody crops and tall grass crops, can be grown on a much wider range of soil types, where the extensive root systems that remain in place with these crops help prevent erosion, and increase carbon storage in soil. Energy crops can often be grown on poorer soil, particularly on sloped land where production of conventional annual food crops is not desirable due to erosion concerns. However, high biomass yields will only be achieved on good soils with sufficient water supply.

Cellulosic biomass is more difficult to break down and convert to liquid fuels, but this tenacity of the material also makes it more robust in handling (with fewer costs for maintaining feedstock quality compared to many food crops). In addition, cellulosic biomass can be easier to store for long periods of time with less deterioration than sugar-based feedstock in particular. Compared to conventional starch and oilseed crops, where only a fraction of the plant material can be used for biofuel production, perennial energy crops can supply much more biomass per hectare of land, since essentially the entire biomass growth can be used as feedstock.

This chapter explores the range of cellulosic biomass supplies that could be used in biofuel production in the coming years. It describes the basic characteristics of cellulosic feedstock and the various supply options, then addresses opportunities to increase cellulose production as an integral aspect of conventional food crop farming. The chapter concludes by addressing energy crop alternatives.

4.2 Basic Characteristics of Cellulosic Biomass

Understanding the basic physical characteristics of cellulosic biomass is helpful in differentiating among the various types of biomass, and their compatibility for producing different biofuels. Cellulosic biomass has three primary components: cellulose, hemicellulose, and lignin. Cellulose has a strong molecular structure made from long chains of glucose molecules with six atoms of carbon per molecule (referred to as 6-carbon sugar). Hemicellulose is a relatively amorphous component that is easier to break down with chemicals and/or heat than cellulose; it contains a mix of 6-carbon (C-6) and 5-carbon (C-5) sugars. Lignin is essentially the glue that provides the overall rigidity to the structure of plants and trees (trees typically have more lignin, which makes them able to grow taller than grasses).

For different types of plants and trees, these three main components of biomass are present in varying proportions. A typical range is 40–55 percent cellulose, 20–40 percent hemicellulose, and 10–25 percent lignin.[1] (See Table 4–1.) To acknowledge its mix of components, cellulosic biomass is often referred to as "lignocellulosic" biomass.

Table 4–1. Physical Composition of Selected Biomass Feedstock

Feedstock	Cellulose	Hemicellulose	Lignin
	(percent)		
Poplar (hybrid)	42–56	18–25	21–23
Switchgrass	44–51	42–50	13–20
Bamboo	41–49	24–28	24–26
Sugar cane bagasse	32–48	19–24	23–32
Hardwood	45	30	20
Miscanthus	44	24	17
Softwood	42	21	26
Corn stover	35	28	16–21
Sweet sorghum	27	25	11

Source: See Endnote 1 for this chapter.

Different technologies for producing biofuels from cellulosic feedstock use different components of the biomass. So-called enzymatic conversion technology focuses on processing the core sugar components of cellulose and hemicellulose into ethanol; the lignin is considered a good boiler fuel or feedstock for the production of various chemicals, fuel additives, or bio-products (such as adhesives). So-called gasification systems, meanwhile, use a gasifier to convert all three main components of biomass to a "syngas," which can then be used to produce liquid fuel such as synthetic diesel, and/or other fuels and chemicals. (See Chapter 5 for a more detailed discussion of biomass-to-liquid fuels (BTL) and other conversion technologies.)

Table 4–2 provides information about the basic chemical content of varying types of biomass feedstock.[2] This content is important in determining a feedstock's suitability for different conversion processes. Agricultural residues, such as sugar cane leaves, tend to be bulkier (lighter weight) and typically have greater amounts of ash than do woody crops like poplar. As a result, this feedstock tends to be more difficult to gasify. Thus, there has been more of a focus on using crop residues or tall grass energy crops for enzymatic conversion to ethanol, particularly since they also tend to have a higher intrinsic sugar content and smaller amounts of lignin. In contrast, woody crops, because of their higher lignin content, are considered a somewhat more attractive feedstock for gasification and conversion to synthetic diesel fuel. However, a given facility will also utilize the cheapest and most available feedstock in its region.

Table 4–2. Chemical Characteristics of Selected Biomass Feedstock

Feedstock	Heating Value (gross)	Ash	Sulfur	Potassium	Ash melting temperature
	(gigajoule/ tonne)	(percent)			(degrees Celsius)
Bamboo	18.5–19.4	0.8–2.5	0.03–0.05	0.15–0.50	
Miscanthus	17.1–19.4	1.5–4.5	0.1	0.37–1.12	1090 [600]]
Hardwood	19.0–21.0	0.5-2.5	0.01–0.04	0.04	[900]
Softwood	19.6–22.4	0.3–1.2	0.01		
Poplar (hybrid)	19.5–19.7	0.5–1.5	0.03	0.3	1350
Switchgrass	18.3–19.0	2.5–7.5	0.07–0.12		1016
Sugar cane bagasse	18.1–19.0	2.8–5.5	0.02–0.15	0.73–0.97	
Sugar cane leaves	17.4	7.7			
Wheat straw	17.4	8.9–10.2	0.16		
Rice straw	18.9	13.4–18.7	0.18		
Corn Stover	17.9–18.5	10.0-13.5	0.06–0.12		
Sweet sorghum	15.4	5.5			

Note: Characteristics vary somewhat for specific samples and field conditions—ranges in characteristics are provided where source data was available for these ranges. Values in brackets for ash-melting temperatures indicate that some initial ash sintering (a sticky pre-melting condition) is observed above the temperatures indicated.

Source: See Endnote 2 for this chapter.

Biomass feedstock that have higher potassium or ash content tend to be more of a problem for gasification technology, since these components can create (or contain) compounds that melt at the high gasification temperatures, leading to potential problems such as slagging or fouling of heat-transfer surfaces. While these are not insurmountable barriers, they do constrain use of this feedstock in a gasifier-based system (whereas enzymatic systems will typically be less affected by potassium and ash content). Ash that melts at a lower temperature can also be a concern for gasification systems, since it tends to be easier to clean up solid particles than sticky half-melted or liquefied material.

4.3 Biomass Residues and Organic Wastes

Biomass residues with potential energy uses are diverse. A distinction can be made between primary, secondary, and tertiary residues and wastes (which are available as a byproduct of other activities) and biomass that is specifically cultivated for energy purposes.[3]

- *Primary residues* are produced during production of food crops and forest products (e.g., straw, corn stalks and leaves, or wood thinnings from commercial forestry). Such biomass streams are typically available “in the field” and must be collected to be available for further use.

- *Secondary residues* are generated during processing of biomass for production of food products or biomass materials. They include nut shells, sugar cane bagasse, and saw dust, and are typically available at food and beverage industries, saw and paper mills, etc.

- *Tertiary residues* become available after a biomass-derived commodity has been used. A diversity of waste streams is part of this category, from the organic fraction of municipal solid waste (MSW) to waste and demolition wood, sludges, etc.

In general, biomass residues and wastes are intertwined with a complexity of markets. Many residues have useful applications as fodder, fertilizer, and soil conditioner, or as the raw material for a variety of products, such as particleboard, medium-density fiberboard (MDF), and recycled paper. Net availability, as well as market prices, of biomass residues and wastes, generally depend on a number of factors, including market demand, local and international markets for various raw materials, and the type of waste treatment technology deployed for the remaining material. The latter is particularly relevant when fees are charged to dispose of the waste, giving some organic waste streams a (theoretical) negative value.

Typically, the net availability of organic wastes and residues can fluctuate and is influenced not only by market developments, but also by variability in weather conditions (causing high and low production years in agriculture), and other factors.

The physical and chemical characteristics of this diverse spectrum of biomass resources also vary widely. Certain streams such as sewage sludge, manure from dairy and swine farms, and residues from food processing, are very wet, with moisture contents over 60–70 percent. (These wet waste streams are typically more suited for producing biogas, rather than ethanol or biodiesel.) Other streams may be more or less contaminated with heavy metals (such a waste wood from construction and demolition) or may have higher chlorine, sulfur, or nitrogen content, depending on the origin or part of the original crop. Clearly, the different properties of biomass resources lead to varying suitability for different conversion technologies.[4]

4.3.1 Wood Residues

Forest Residues

Over the last century, human efforts to control or limit forest fires have generally been quite successful. However, this has often led to an excess amount of undergrowth in forests (in the form of small diameter trees, etc.) that creates imbalances in the health of a forest. Some amount of “understory” management can help improve the health and productivity of forests, typically entailing thinning and removal of the excess build up of small-diameter woody growth. However, the cost of removing this growth has often been too high to justify the investment.

Creating a market for this woody undergrowth for use in biomass-to-liquid (BTL) fuel applications may complement efforts to create healthier forests. Some amount of treetops and limbs that result from traditional logging industry activities may also be suitable as a supply of wood for biofuel production; however, the amount of woody material that should be kept in the forest for habitat and carbon storage needs must be evaluated before the wood is removed. Wood from pest or storm damaged forests could also be a potential source of biomass for biofuel applications.

Industrial and Urban Woody Residues

Much of the wood residues produced by the lumber industry are used to provide the energy needed for the lumber production process (such as lumber drying and cogeneration of heat and power), though some of this wood may be available for biofuel uses.

The pulp and paper industry tends to use much of its wood waste as boiler fuel in producing biomass. However, the "black liquor" residue that results from the pulping process requires expensive boilers for disposal and could be a potential source of biofuel feedstock. (The cellulose from wood is used to make paper, but the hemicellulose is contained in the black liquor.) There has been an increasing interest in using black liquor residues for producing ethanol in the near term, since there are substantial amounts of C-5 and C-6 sugars in this residue resulting from the hemicellulose portion of the woody feedstock used for pulping. For example, the U.S. Department of Energy has been co-sponsoring development efforts with the paper industry in an effort to foster the production of ethanol fuel from black liquor residues.[5]

Wood from urban tree trimming from yards and rights-of-way has various competing uses, such as the production of mulch, or for electric power production or thermal energy needs; however, some of this wood may be available for use in biofuel production. (See Chapter 6 for more discussion on competing uses for biomass resources.)

4.3.2 Municipal Solid Waste

A mix of cellulosic waste material is typically present in municipal solid waste, including wood, paper, cardboard, and waste fabrics. Since fees are typically charged to dispose of this waste, it could provide a supply of low or "negative cost" biomass for some early pioneer cellulose-to-biofuels facilities in urban areas. Such facilities will have to overcome legal barriers and public reluctance to accept waste processing near populated areas.

4.3.3 Crop Residues

Crop residues in the form of stems and leaves from conventional food crop harvests represent a substantial quantity of cellulosic biomass produced each year. In many instances, much of this residue needs to be left in the field to provide protection from erosion and to provide benefits such as micronutrient supplies, soil organic matter, and enhanced soil "tilth" (the texture, structure, and pore spacing in soil). However, in cases where land is relatively flat and/or where conservation tillage methods are employed, a portion of the crop residues may be sustainably harvested. Table 4–3 provides estimates of crop residues produced for various conventional crops.[6] It indicates the total amount of residues produced, before taking into account site-specific limitations on the amount of residues that can be sustainably removed. Residues for rapeseed and soybean residues are not sufficient to warrant collection, in part because current varieties of these plants deteriorate too quickly.

Driven by a need to reduce erosion, maintain soil structure and nutrients, and build soil carbon levels, agriculture has increasingly adopted more-sound environmental and conservation practices. One increasingly popular option is no-till cultivation, where the soil is left undisturbed from harvest to planting (with only a narrow slot or drill hole used to plant seeds) and weeds are typically controlled with herbicides. No-till cultivation is now practiced on more than 25 million hectares in the United States, representing nearly 23 percent of the country's planted cropland area in 2004.[7] On highly productive land, these practices increase the amount of crop residues that can potentially be collected for certain types of crops. For example, no-till cultivation may allow harvesting of as much as 75 percent of corn stover (the stalks and leaves remaining on corn plants) where land slope and erosion problems are minimal.

Table 4–3. Agricultural Residues from Conventional Crops

Crop	Residue Amount (dry tonnes/hectare)	Range in Straw Residues per Tonne of Grain Harvested (tonnes)
Corn	~10.1	0.55–1.50
Sorghum	~8.4	0.85–2.0
Cotton	~6.7	0.95–2.0
Rice	~6.7	0.75–2.5
Wheat	~5	1.10–2.5
Barley	~4.3	0.82–2.50
Rapeseed	–	1.25–2.0
Soybeans	–	0.8–2.6

Note: Ranges reflect factors such as different crop varieties, levels of soil fertility or fertilization, rainfall and water availability, etc.
Source: See Endnote 6 for this chapter.

There are long-term economic and environmental concerns associated with the removal of large quantities of residues from cropland. Removing any residue on some soils could reduce soil quality, promote erosion, and lead to a loss of soil carbon, which in turn lowers crop productivity and profitability. On other soils, some level of removal can be sustainable and even beneficial. A substantial amount of research has been conducted to evaluate sustainable levels of crop residue removal, and additional research is needed to help further establish criteria under many circumstances. Establishment and communication of research-based guidelines is necessary to ensure that removal of residue biomass is done in a sustainable manner.[8] (See Chapter 12 for more on soil quality concerns.)

Corn Stover and Wheat Straw

As indicated in Table 4–3, corn crops typically produce the largest amounts of crop residues per hectare of all of the main conventional crop types (these residues, known as stover, include the stalks, leaves, and cobs of the plant after the grain is harvested). Since large amounts of corn are often grown in specific geographic areas, such as the U.S. Midwest, the aggregate supply of corn stover may be plentiful in these areas, probably representing one of the best near-term options for abundant cellulosic feedstock for ethanol production. In other places, particularly Canada and Europe, wheat straw is a more abundant potential cellulosic feedstock.

With either stover or straw, more could be harvested if no-till cultivation methods are adopted. Because they release less soil carbon, such techniques allow a greater portion of the crop residue to be harvested for biofuel use, since less stover or straw would be needed to protect the soil from erosion and carbon losses.

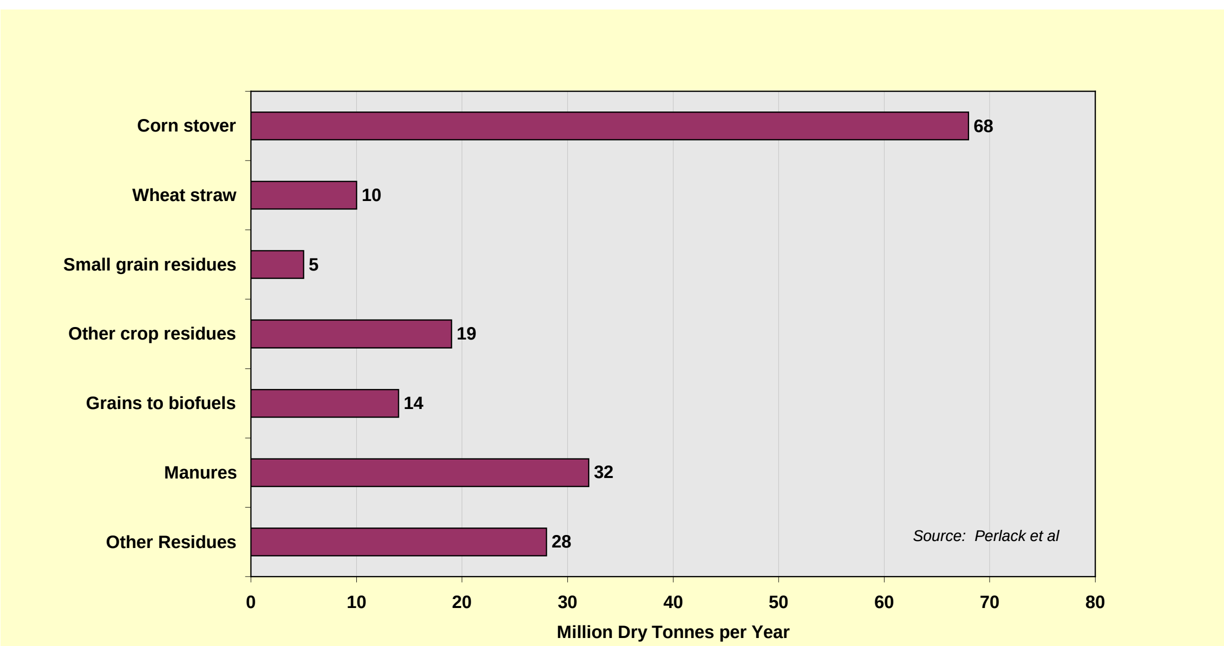
Sugar Cane Residues

In Brazil, more than 80 percent of the sugar cane harvest is cut manually.[9] Before this cutting occurs, the tops and leaves of the cane are typically burned off to make harvesting safer and more productive for workers. However, plans are advancing to mechanize the cane harvest to avoid burning of fields, a practice that causes considerable air pollution. (See Chapter 12.) The state of São Paulo has set deadlines for eliminating the use of fire in crop management, and 25 percent of the state's cultivated area is now harvested mechanically.[10] Technological evolution is gradual, however, requiring development of realistic policies for recycling and redeploying labor and for monitoring the environmental impacts of erosion and spread of pests that follows mechanization.

As technologies for converting cellulose to biofuels are commercialized, this should create markets for the cellulosic field residues (tops and leaves) from sugar cane harvesting. This could significantly expand the supply of feedstock available for biofuel production in the tropical areas where sugar cane is produced, while facilitating significant reductions in air pollution caused by the burning of cane fields.

In addition, the commercialization of cellulose-to-ethanol technology could expand the supply of cellulose available for ethanol production by allowing the use of bagasse residues (the cellulosic plant stalks/residues left after extracting sugar from the cane stalks, which is currently burned in boilers for process heat) to be used for ethanol production instead. The lignin residues that remain after processing the bagasse could then be used as boiler fuel (depending on the demands for process heat and alternative markets for electricity production from bagasse boilers).[11]

Figure 4–1. Estimated Availability of Sustainable Agricultural Residues in the United States



A fairly detailed evaluation of the amount of agricultural residues that could be sustainably collected each year for use in bioenergy applications has been done for the United States, as summarized in Figure 4–1.[12] These estimates are based on current tillage practices using existing harvesting technology. The “other residues” category includes municipal solid waste and animal fats. The combined total supply of sustainable residues available in the United States is about 175 million dry tonnes per year.

Improved Crop Residue Collection Technology

Most residue recovery operations today pick up residue left on the ground after primary crops have been harvested. Collecting these residues involves multiple passes of equipment over fields and results in no more than 40 percent removal of stover or straw on average.[13] This low recovery amount is due to a combination of collection equipment limitations, contour ridge farming, economics, and conservation requirements. It is possible under some conditions to remove as much as 60–70 percent of corn stover or straw with *currently available* equipment. However, this level of residue collection is economically or environmentally viable only where land is under no-till cultivation and crop yields are very high. This analysis assumes that the efficiency of harvest technology and the percentage of cropland under no-till management are increased simultaneously.

Certain components of crop residues are more valuable than others; the components that should be left on the field to address sustainability and erosion concerns vary depending on climate and growing conditions and on the crop. Selective harvest technologies could have the ability to leave much of the desired residue components on the field for soil enhancement and erosion protection, and harvest only the portion of residues that sustainable crop management will allow.

Future residue collection technology with the potential of collecting up to 75 percent of the residue is envisioned. These systems are likely to be single-pass systems that would reduce costs by collecting the grain and residue together. Single-pass systems will also address concerns about soil compaction from multiple pieces of residue collection equipment, unless the single-pass system is heavier than the current grain harvesters. Further, one-pass systems for corn and grain will need to have selective harvesting capability so that some portions of the residue stream can be reapplied to the field to meet site-specific conservation requirements.[14]

4.4 Increasing Cellulose Yields from Grain and/or Oilseed Crops

Dramatic increases in the yields of major food crops have been a direct result of research such as corn and wheat hybridization. These crop development efforts have naturally focused on increasing the amount of food produced, while often attempting to reduce the quantity of stems and leaves produced, since these were not the desired product. As markets develop for cellulose for the production of biofuels (along with new technologies for converting this type of plant material into biofuels), food crops that also produce significant quantities of cellulosic residues could increase farmer revenues, and increase the overall output of each hectare of farmland.

It is possible to do selective breading of starch, sugar, and oilseed crops, where new plant varieties could be specifically developed to increase the amount of cellulose (i.e., more stem and leaf volume) that is produced along with the food crop, allowing for significant cellulose harvesting in addition to the primary food crop harvesting.[15] (See Sidebar 4–1.)

Sidebar 4–1. Crop Options to Increase Cellulose Residues

A change in the residue-to-grain ratio is a possible technology change that could occur for any crop. Indeed previous breeding efforts have reduced the residue-to-grain ratio. Consider the case of soybeans. Most, if not all, soybean residue currently needs to be left on the ground to meet conservation practice requirements. A genetic improvement research program on soybeans is being conducted by the U.S. Department of Agriculture that focuses on developing varieties that have a higher ratio of straw to beans, grow taller, have improved lodging resistance, have a better over-winter residue persistence, and are able to attain these traits without genetic transformation.

Originally, the soybean program was geared to develop larger biomass soybeans for forage production and resulted in three varieties. A recently released variety for the southeast, Tara, has the characteristics of a 1.75 residue-to-grain ratio without sacrificing expected levels of grain yield. It is evident from data on the forage soybean varieties that the potential exists to produce 100-percent more crop residue and thus provide more soil conservation benefits than the conventional varieties. It cannot be predicted whether farmers will adopt these new varieties, but clearly the technology will be available. Potentially, with such varieties soybean acreage could contribute to the availability of residues for the production of biofuels – increasing biofuel production without using additional land.

Source: See Endnote 15 for this chapter.

It may also be possible to modify crop cultivation and management approaches with the intent of increasing the amount of cellulosic crop residue supplies that can be harvested, through means such as increasing plant-spacing densities to maximize the combined yield of food and fiber. Food yields may go down somewhat with increased plant densities, but the total amount of crop residues produced per hectare would increase.

4.5 Double-Cropping Approaches

As markets develop for cellulose use in the production of biofuels, new approaches for growing more than one crop per year on farmland could significantly increase the amount of biomass produced per hectare of land each year. In traditional approaches for producing food crops, vigorous plant growth occurs in the spring as the stems and leaves quickly grow to create the plant structure that will then work to produce the final food crop (grain, oilseed, etc.). If the goal is to obtain maximum yields of cellulose rather than the end "fruit" of the plant cycle, however, an entirely new strategy can be used for crop planting and harvesting. One such strategy, "double cropping," has been particularly successful in Germany. (See Chapter 19.)

Winter wheat crops planted in the late fall, for example, could be harvested much earlier in the following year if is not necessary to wait for the grain to form and mature. This cellulose in the form of tall, grassy wheat stems and leaves could be harvested and sold for use in the production of biofuels. A second crop could then be planted (such as legumes that fix nitrogen in the soil) early enough in the year to mature for fall harvesting. Research and evaluation could determine the best combination of crops to grow for the first and second cycle of planting and harvesting each year to maximize the output and revenue that farmers obtain from each hectare of land; the best combination might be to produce just cellulose, or a combination of cellulose and food crops, depending on the local climate, soil type, and market considerations.

4.6 Energy Crops

Large amounts of cellulosic biomass could be produced via dedicated plantations of energy crops, based on the use of perennial herbaceous plant species (such as various tall grass species), or with the use of “short-rotation” (i.e. fast-growing) woody crops, also known as SRWC.

There has been some use of SRWC for industrial purposes: for example, eucalyptus trees have been grown for pulp markets and to supply charcoal for the steel industry in Brazil, and in Europe and the United States, poplar trees have been grown to provide fiber for the pulp and paper industry. In general, however, efforts to evaluate and develop energy crops are still in a relatively early stage of development when compared to conventional crops where plant breeding has been under way for many years. The relatively early phase of energy crop development reflects a situation where tremendous opportunities exist to use advanced plant science and agronomy to dramatically increase biomass yields.

There are a number of reasons why energy crop production could be quite attractive, beyond offering the potential to substantially expand the supply of biomass feedstock. The conversion of land from intensive annual crop production to perennial herbaceous species, or to SRWC, progressively increases the soil’s organic matter content—whereas the conversion of land from natural cover to intensive annual crop production on farms typically decreases the organic matter content of the soil over time. The roots of the perennial crops provide protection from erosion, and the crops generally require less-intensive use of fertilizers and pesticides, as well as less overall energy consumption for crop management (especially since it is not necessary to plow the land each year to do new crop planting).

Willow is a good example of a tree species suitable for use as a SRWC in temperate climates. Willow trees can achieve high biomass yields using a short-rotation coppice (SRC) approach. Short-rotation coppicing entails harvesting the aboveground growth of young trees, where the vigorous new growth of shoots and branches from the remaining tree trunks are then harvested every few years. In the case of SRC-Willow energy crops, the new growth is harvested every 2–5 years over a period of some 20–25 years.

Most experience with SRC-Willow systems in Europe has been in Sweden, where this crop is produced on some 14,000 hectares. A substantial amount of development work has also been conducted on SRC-Willow crops in New York in the United States. Willow crop yields have increased significantly due to research on genetics and breeding, with yields for some varieties doubling (or more) as a result. Hybrid poplar trees are also well suited to SRC energy crop applications.

As noted above, eucalyptus plantations have been grown in tropical regions for a variety of industrial uses. In the 1970s and early 1980s, a SRC approach was used for the initial eucalyptus plantations grown in Brazil. The tree stands were harvested every 5–7 years, for up to three rotations before replanting. However, over this time frame they found that problems occurred with diseases and pests, and the planted tree species were ultimately not as robust as newer clones and hybrids that were developed during the coppice periods. To take advantage of the fast pace of eucalyptus species improvements, the current practice in Brazil is generally to plant new improved hybrid eucalyptus varieties after the first harvest. It should also be noted that eucalyptus can absorb larger quantities of water from water tables.[16]

Tall grass species such as miscanthus, switchgrass, and reed canary grass are also examples of perennial crops that can be harvested every year. They have been the focus of considerable interest in Europe and North America. Some experts believe breeding could result in at least a doubling of the productivity of energy grasses. With varieties such as Bermuda grass and Pensacola Baha grass, yields have been increased by twofold and sevenfold.[17] Research suggests that future gains in switchgrass productivity, through an aggressive breeding program, could increase average yields per hectare to more than 17 dry tonnes by 2025, and nearly 28 dry tonnes by 2050, even without using genetically modified plants.[18] Although they assume adequate soils and sufficient water, such advances will not be as complicated as breeding food crops since it is easier to breed for size rather than for a particular quality, such as taste in fruits or vegetables. While commercial production of perennials as energy crops is currently negligible, their future potential is expected to be quite large, particularly as conversion technologies are commercialised that can economically produce biofuels from this cellulosic feedstock.[19]

In general, dedicated biomass production is more expensive per unit of energy produced than the use of available residues and wastes. Typical cost ranges for perennial woody crops under northwestern European conditions are €3–6 ($3.6–7.3) per gigajoule (compared to some €1–2, or $1.2–2.4, per gigajoule for imported coal). Biomass production costs of dedicated production systems are especially dependent on the costs of land and labor and the (average) yield per hectare. Typically, land costs (e.g. through land rent) can contribute about one-third of the total biomass production costs under northwestern European conditions.

Both land and labor are relatively expensive production factors in Europe, a tendency that is maintained indirectly by structural agricultural subsidies under the EU's Common Agricultural Policy (CAP). In addition, agricultural surpluses in the EU are partially counteracted by measures to take agricultural land out of production (i.e., classified then as set-aside land). This land category could in theory be available for energy crop production, but the total set-aside land surface varies over the years (from 10 percent to less than 3 percent of the arable land) and is generally taken up in typical rotation systems of farmers, making introduction of perennial crops difficult. This partially accounts for the relative popularity of annual crops for energy purposes (such as rapeseed and interest in hemp).[20]

Table 4–4 summarizes the performance characteristics and developmental status of four potential energy crops considered for short- and long-term uses in temperate climates: short-rotation willow, short-rotation hybrid poplar, miscanthus, and switchgrass.[21] Commercial experience with SR-Willow has been gained in Sweden and the United States, and to a lesser extent in the United Kingdom and other countries. In Eastern Europe there has been major interest in producing willow trees as an energy crop, where conditions are well suited and where low costs can be achieved on a somewhat longer term. Short-rotation hybrid poplar, meanwhile, is well suited to deliver both biomaterial and energy fractions as a typical multi-product system. The economics of producing the tree depends on the production region as well as market prices for the material produced. So far, there has been only limited commercial experience with miscanthus (in Europe), and the breeding potential of the species has hardly been explored.

Table 4–4. Performance Characteristics and Developmental Status of Four Potential Perennial Energy Crops

Energy Crop	Description	Typical Rotation	Typical Annual Yield (dry tonnes per hectare)	Price (Euros per gigajoule)	Suitable Climate
Short-Rotation Willow	perennial tree crop	3–4 years	10 (next 10 years) 15 (in 10–15 years)	€3–6 (next 10 years) €2 or less (in 10–15 years)	colder and wetter
Short-Rotation Hybrid Poplar	tree planted for pulpwood in various countries	8–10 years	9 (next 10 years) 13 (in 10–15 years)	€3–4 (next 10 years) €2 or less (in 10–15 years)	temperate climates
Miscanthus	perennial tall grass crop	harvested annually	10 (next 10 years) 20 (in 10–15 years).	€3–6 (next 10 years) €2 (in 10–15 years)	both temperate and warm (yields highest in warm climates)
Switchgrass	perennial tall grass crop	harvested annually	12 (next 10 years) 16 (in 10-15 years).	€3–4 (next 10 years) €2 or less (in 10–15 years)	temperate climates

Source: See Endnote 21 for this chapter.

4.7 Habitat and Mono-crop Issues

Compared to conventional annual farm crops, energy crops can provide a friendlier habitat for some forms of wildlife, in that all of the vegetation on energy plantations would not necessarily be removed each year. In addition, the density and height of energy crop vegetation is likely to be greater than for conventional annual row crops. One approach that could help reduce the impacts of harvesting on wildlife would be to harvest during non-nesting periods, and to harvest in alternating strips of crops so that animals can move to an adjacent strip of crop area that will not be harvested that season. (Habitat and mono-crop issues are discussed further in Chapter 12.)

Research is needed to determine whether some mixing of varied grass or tree species could be allowed on energy plantations in an effort to add some variety in the vegetative landscape. This would likely entail special considerations regarding harvesting and conversion technology that could accommodate the variations in feedstock. This added variety in energy crop species may well tend to decrease the maximum crop yields that are achieved; however, cost-benefit analyses could help determine the impacts on the feedstock production costs in comparison to the wildlife habitat benefits provided by added plant diversity.

4.8 Conclusion

As new technology for converting cellulose to biofuels is commercialized, vast supplies of waste biomass could be available for the production of liquid transportation fuels. Potential constraints on the ability to use these resources will include competing uses for fiber, and environmental constraints regarding soil and habitat sustainability. The lowest-cost supplies, with potentially no cost or even negative costs (such as with municipal solid waste, where tipping fees are paid to dispose of the waste), will be an early source of cellulosic biomass used to produce biofuels.

Crop residues are anticipated to supply an increasing amount of biomass for use in biofuel production. Research and development will be needed to better understand soil and crop dynamics in relation to residue removal practices, and improved harvesting and handling equipment will need to be developed that can collect crop and forest residues. For crop residues, harvesters that result in minimal soil compaction and minimal interruption of primary food crop harvests are desirable (these harvesting operations typically must be completed within a tight “window” of time, before weather damage occurs to crops, and before crops begin to deteriorate).

Further research and development is needed on perennial energy crops, including willow, hybrid poplar, eucalyptus, miscanthus, and switchgrass, in an effort to improve yields, refine crop management techniques, and refine harvesting and handling equipment. Given the amount of time that will be necessary to develop, demonstrate, and commercially deploy energy crops, these crops need to be developed under various conditions worldwide as soon as possible, in order to assure that feedstock supplies using these crops will be available in the medium term (i.e, in the next 8–15 years). In order to improve the economics of energy crop production, research is also needed for related systems, such as densification of crop residues and tall grasses; optimization of feedstock storage methods; and transport systems for biomass.

The widespread establishment of perennial energy crops has the potential to significantly reduce net carbon emissions from transportation fuel use, reduce soil loss from erosion, reduce agro-chemical run-off, create improved habitat, create jobs, and increase domestic energy supplies and national security. Trade-off analyses are needed to determine whether some amount of diversity can be included in the variety of energy crops grown on plantations, in an effort to enhance habitat resulting from energy plantation development.

Chapter 5. New Technologies for Converting Biomass into Liquid Fuels

5.1 Introduction

The use of “next-generation” cellulosic biomass feedstock has the potential to dramatically expand the resource base for producing biofuels in the future. Technology development efforts to date have demonstrated that it is possible to produce a variety of liquid fuels from cellulosic biomass, for use in existing vehicles. So far, however, the costs of producing liquid fuels from cellulosic biomass are not competitive with petroleum-derived fuels, even with the recent rise in petroleum costs. Various government and industry-sponsored efforts are under way to lower the costs of making liquid fuel from cellulosic biomass by improving the conversion technologies.

This chapter describes the basic technology options available for converting cellulosic biomass into biofuels and evaluates the prospects for their implementation.

5.2 Basic Conversion Technology Options

A key characteristic of cellulosic biomass resources is that they are naturally resistant to being broken down into their constituent parts, particularly in comparison to first-generation biomass feedstock such as starch, sugar, or vegetable oil. Thus, while the cost for cellulosic feedstock itself is expected to be lower than for current feedstock, the difficulty of converting this next-generation feedstock to liquid fuel means that the conversion technologies are prone to being more expensive than current conversion technologies.

To overcome the recalcitrant nature of cellulosic biomass, multiple steps are generally required to convert it into liquid fuel. The two primary pathways for producing liquid fuels from biomass are thermochemical conversion and biochemical conversion.

5.2.1 Thermochemical Conversion

There are two main thermochemical pathways for converting biomass into liquid fuel. The first is to gasify cellulosic biomass in a high-temperature vessel where oxygen levels are kept low enough to prevent the resulting combustible gases from burning. The so-called “syngas” produced in this intermediate step is then converted to liquid transportation fuel using advanced catalyst conversion (such as Fischer-Tropsch technology, described later in this chapter). The production of synthetic diesel fuel has been a primary focus with this approach.

The second thermochemical pathway for converting biomass into liquid fuel is pyrolysis, which, similar to the gasification pathway, uses high temperatures in the absence of oxygen to convert the biomass into liquid “bio-oil,” solid charcoal, and light gases similar to syngas. Pyrolysis is done at about 475 degrees Celsius, whereas gasification is done at temperatures of 600–1,100° C.[1] Bio-oil is moderately acidic with a water content typically in the range of 20–25 percent; it does not mix well with petroleum products and is generally best suited for use as a fuel for stationary electric power or thermal energy applications, rather than as a transportation fuel.

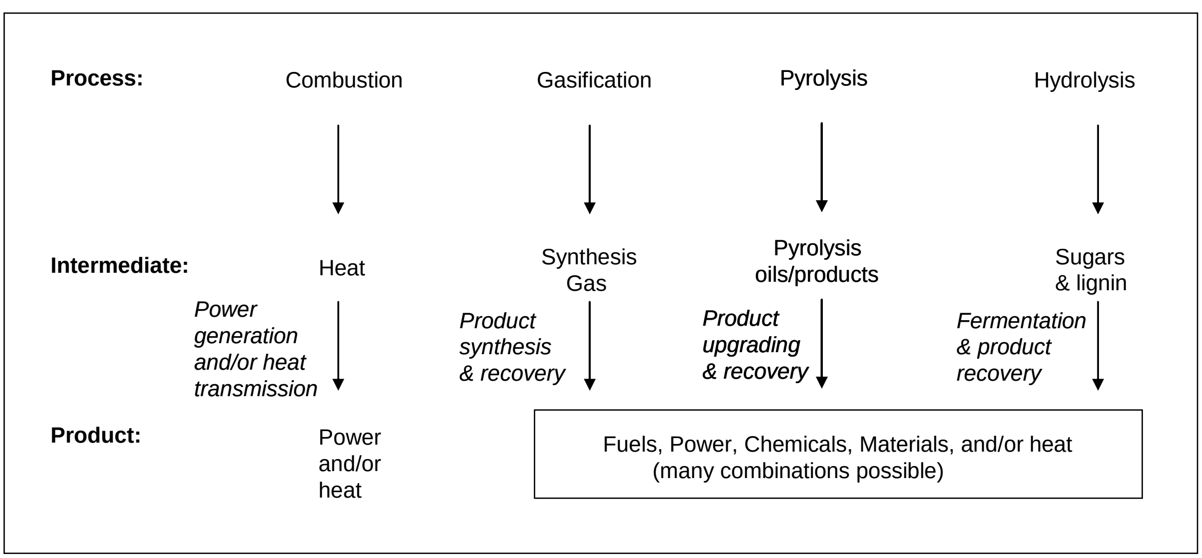
5.2.2 Biochemical Conversion

The other basic pathway for converting cellulosic biomass into liquid fuel is biochemical. It involves breaking down the biomass into its component sugar molecules, followed by the use of fermentation organisms (specialized bacteria or yeasts) to biologically convert the sugar into ethanol fuel. This pathway requires an initial pretreatment phase (for example, using steam and/or acid) to break down the biomass into a liquid slurry of its component parts—cellulose, hemicellulose, and lignin.

The pretreatment conditions are typically sufficient for breaking down the hemicellulose component into its basic molecules of sugar (a mix of five-carbon and six-carbon sugars, as described in Chapter 4). However, breaking down the cellulose component into its sugars (glucose) is more difficult, requiring an additional step in the conversion process. This has been accomplished by using either concentrated acid and low temperatures, or dilute acid at higher temperatures. At present, however, the use of customized enzymes (known as cellulase enzymes) is generally viewed as the most promising way to break down the cellulose into glucose.[2]

Fermentation organisms are readily available for converting glucose to ethanol. However, the sugar molecules produced from hemicellulose (particularly the C-5 sugars) have required the development of customized fermentation organisms to enable their conversion to ethanol. With modern advances in biotechnology it is possible to substantially customize and enhance the performance of enzymes for specialized conversion applications. Much of the research funding for improving the biochemical conversion pathway has focused on either improving fermentation organisms or improving the performance of the cellulase enzymes used to convert cellulose to glucose, and reducing their costs. (Note that the lignin component of the biomass is separated from the slurry and can be used in a variety of ways, for example as boiler fuel to provide steam and electricity for the conversion process, or further processed to make products such as adhesives, fuel additives, etc.)[3]

Figure 5–1. Lignocellulose Processing Pathways



Researchers are also developing variations and combinations of thermochemical and biochemical pathways for converting biomass resources into useful energy products. Four primary pathways for bioenergy production are highlighted in Figure 5–1.[4] Combustion and pyrolysis are two thermochemical pathways that can be used to produce electricity and/or provide thermal energy for applications such as industrial processes or space heating. Whereas gasification (another thermochemical pathway) and hydrolysis (a biochemical pathway) can provide a variety of products, the production of liquid fuels for transportation uses is a primary focus of this report. Thus the following chapters focus mostly on these two pathways.

The various conversion pathways are described in greater detail in the following sections.

5.3 Converting Lignocellulosic Fibers and Wastes into Liquid Fuels

5.3.1 Gasification and Fischer-Tropsch (F-T) synthesis

The gasification of biomass has been possible for much of the last century. Gasification followed by synthesis to liquid fuels was first applied to coal in Germany during the 1920s, using technology developed by German researchers Franz Fischer and Hans Tropsch (hence the technology is known as the Fischer-Tropsch, or F-T, process). During World War II, Germany as well as Japan produced diesel fuel from coal due to shortages of petroleum supplies. Later, South Africa used coal-to-liquid (CTL) technology in response to international embargoes on petroleum. For fuel synthesis, other processes are also under consideration, e.g. the methanol-to-synfuel route.

Using gasification technology, biomass is converted to a mixture of carbon monoxide, carbon dioxide, hydrogen, and methane—commonly referred to as synthesis gas, or "syngas"—by heating it in the presence of limited oxygen. Syngas can be converted to a variety of fuels such as hydrogen, methanol, or dimethyl ether (DME), as well as synthetic diesel and gasoline (via the F-T process). In principle, numerous process configurations exist for gasification-based conversion of biomass to fuels, depending, for example, on the gasifier type, the gas cleaning process, the product fuel, and whether electricity is cogenerated using part of the syngas output from the gasifier.[5]

When applied to biomass, a key advantage of the gasification pathway is that it can convert all of the organic matter in biomass into gases and then liquids. In particular, the lignin component of biomass, which enzymes can hardly crack, is readily gasified and made available as a fuel feedstock. Gasification and F-T synthesis thus has the potential to produce more fuel per tonne of biomass.[6]

However, the gasification/F-T pathway has so far remained too expensive to be economical. During the 1980s, a number of biomass gasification projects sprouted in France, Sweden, and Finland, which mostly produced methanol from wood and wood wastes, but lower petroleum prices and cheaper methanol eventually undercut these operations.[7] In particular, the capital costs of construction have proven prohibitive.[8] But keeping the gases and equipment clean has represented another key obstacle. The gas produced from gasification also contains tars, fine particles, alkali compounds, and halogens that can clog filters, poison catalysts used in downstream fuel synthesis, or corrode the gas turbine used in electricity cogeneration. Thus, techniques for cleaning the syngas are an important requirement for successful operation of these systems.[9]

As of early 2006, there were no commercial plants producing lignocellulosic biomass-derived liquid fuels via gasification, but demonstration efforts are well under way. Pilot and demonstration units producing electricity via biomass gasification were under development in Scandinavia, the United States, Brazil, and the European Union.[10]

5.3.2 Pyrolysis

Variations of pyrolysis, which puts biomass under heat at very low levels of oxygen, have existed as well but are not employed on a large scale. Depending on the operating conditions (temperature, heating rate, particle size, and solid residence time), pyrolysis can be divided into three subclasses: conventional, fast, or flash. To maximize bio-oil production, fast/flash pyrolysis is used, heating the biomass at about 500° C for less than ten seconds.[11]

Several challenges must be overcome before biomass pyrolysis can become a commercially viable means to produce energy on a large scale. Pyrolysis oils have several undesirable characteristics that necessitate downstream processing. For instance, they contain suspended char and alkali metals that can damage engines. They are acidic, temperature-sensitive, and highly viscous, which can also cause storage and engine problems.[12] They also typically contain 20–25 percent water (contributed by the water in the initial biomass and from the conversion process). With proper treatment, however, pyrolysis oils can be used in many applications, such as combustion in boilers, stationary diesel engines, industrial combustion turbines, and Stirling engines (which are external combustion engines used to produce heat and power). The comparative option of upgrading these oils for vehicle engine use does not appear promising.[13]

As of early 2006, there were no large-scale biomass pyrolysis facilities, though several smaller facilities were in operation. Ensyn Technologies in North America has built several small commercial plants geared toward production of specialty products (e.g. natural resins, co-polymers, and other chemicals). DynaMotive Energy Systems in Vancouver, Canada, recently opened a 100-tonne per-day facility to produce fuel for combined heat and power production at a wood products plant in Ontario.[14] Biomass Technology Group (BTG), located in the Netherlands, has demonstrated its rotary cone reactor technology at the five-tonne per-day scale, with plans to build a 50-tonne per-day plant.[15] Notably, pyrolysis oils are not currently used for transportation.

It should be noted that biomass can also be converted into a liquid oil by direct hydrothermal liquefaction, which is a form of intermediate pyrolysis that occurs in the presence of water.[16] Hydrothermal treatment is based on early work performed by the U.S. Bureau of Mines' Albany Laboratory in the 1970s. Developers include Changing World Technologies (West Hampstead, NY); EnerTech Environmental, Inc. (Atlanta, GA); and Biofuel B.V. (Heemskerk, the Netherlands).[17] In particular, the oil company Royal Dutch Shell has experimented with a process called hydrothermal upgrading (HTU) which also yields a synthetic diesel fuel from wet biomass.[18]

5.3.3 Acid Hydrolysis

In the early part of the 20th century, the Germans developed an industrial process for converting biomass into ethanol that used dilute acid to hydrolyze cellulose to sugars. This acid hydrolysis process was soon adopted in the United States, resulting in the operation of two commercial plants during World War I.[19] Commercial processes using concentrated sulfuric acid were in operation in the 1940s, particularly in the former Soviet Union and Japan. These plants, however, were only successful during times of national crisis, when the economic competitiveness of ethanol production could be ignored.

Today, only a few acid hydrolysis facilities exist. Arkenol operates a 1-tonne per-day pilot facility that uses concentrated acid hydrolysis.[20] A few acid hydrolysis facilities have also been operating in Russia, which use inefficient technology to produce ethanol for industrial uses. Smaller demonstration facilities also exist at universities and government labs such as Lund University (Sweden), the Danish Technical University, and the U.S. National Renewable Energy Laboratory.[21]

Using acid to hydrolyze lignocellulosic fibers has not been as economical as hydrolysis of starches or the simple fermentation of sugars. Processes that hydrolyze fibers with dilute acid and pressure have tended to degrade too much of the hemicellulose sugars before they can be fermented into ethanol, causing low yields.[22] The other option, using concentrated acid at lower pressures, has required purchasing and then recycling expensive quantities of acid.[23]

5.3.4 Enzymatic Hydrolysis and Microbial Digestion

The prospect of using enzymes instead of acid to hydrolyze fibers into sugars has generated much greater enthusiasm. Enzymatic hydrolysis of conventional starchy feedstock has already replaced acid hydrolysis in ethanol facilities in the United States.[24] The next step would be to apply similar enzymes to cellulose and hemicellulose fibers. Since cellulose is more difficult to digest than hemicellulose, enzymes' effectiveness at hydrolyzing cellulose has been identified as a limiting factor.

Another limiting factor has been the inability of yeasts to digest some of the sugars contained in hemicellulose. Typically, the sugar that results from hydrolyzing starch and cellulose contains six carbons (glucose and mannose), which are familiar to conventional fermentative yeasts. Hydrolyzing hemicellulose, however, yields a combination of both six-carbon sugars and five-carbon sugars, and normal yeasts cannot ferment the five-carbon ones. Since a third or more of the total carbohydrate content of typical biomass is comprised of five-carbon (or "pentose") sugars, it is highly desirable that these be fermented.[25]

Research and development on conversion of pentose sugars to ethanol has been a major focus over the last 15 years, and has resulted in several promising strains. These include strains of enteric bacteria (*Esherichia coli, Klebsiella oxytoca*), thermophilic bacteria, the mesophilic bacterium *Zymomonas mobilis*, and yeast.[26]

Iogen Corporation, a consortium of PetroCanada and Royal Dutch Shell, currently uses related microorganisms at a test facility in Ottawa, Canada, but they can only produce ethanol for €0.44–€0.66 per liter ($0.53–$0.79), in comparison to about €0.24 per liter ($0.29) for conventional ethanol.[27] The rapid development of this technology is covered in the following section.

5.3.5 Status of Next-Generation Conversion Technology

During the early 2000s, the price of petroleum has risen again, and many expect it to remain higher than €35 ($42) per barrel. Sustained high oil prices are making next-generation conversion technologies more viable, prompting further development of older sulfuric acid processes, as well as continued refinements in the newer biological and thermochemical pathways.

Processes that hydrolyze lignocellulosic fibers with acids are gaining some renewed interest. Arkenol, a leader in advanced sulfuric acid hydrolysis, is planning the construction of several new facilities in the United States. Similarly, the primary supplier of equipment for Brazil's sugar and ethanol mills, Dedini, is developing its own sulfuric acid process for converting sugar cane bagasse fibers into ethanol.[28]

In the United States, the 2005 Energy Policy Act set a priority on the production of cellulosic biofuels, setting a national target of 250,000 gallons (946,000 liters) of cellulosic ethanol production by 2012. In early 2006, the government offered €132 million ($160 million) in incentives to build up to three industry-government funded cellulosic ethanol refineries, and the Department of Energy has a larger budget for researching biomass alternatives to petroleum.[29] In the European Union (EU), converting lignocellulosic matter into liquid fuels has been identified as a priority in the EU Biomass Action Plan.[30]

Various efforts are under way to estimate the anticipated costs for biofuels in the future as progress is made in making advanced "next-generation" biofuels less expensive. Figures 5–2 and 5–3 summarize the results of an International Energy Agency study that estimated the costs of biofuels after the year 2010, comparing both first-generation and next-generation technologies for producing gasoline and diesel substitutes.[31] The lowest cost biofuels are expected to continue to be ethanol produced from sugar cane and biodiesel produced from recycled cooking oil and waste grease. Beyond these two least cost options, the costs for producing next-generation biofuels are expected to be in a range that should make them generally competitive with first-generation technologies. As noted earlier, the ability of next-generation technologies to use abundant cellulosic feedstock that do not rely on food crops offers the promise of dramatically expanding the amount of biofuels that could be produced for transportation needs in the future.

Figure 5–2. Cost Ranges for Ethanol Production After 2010

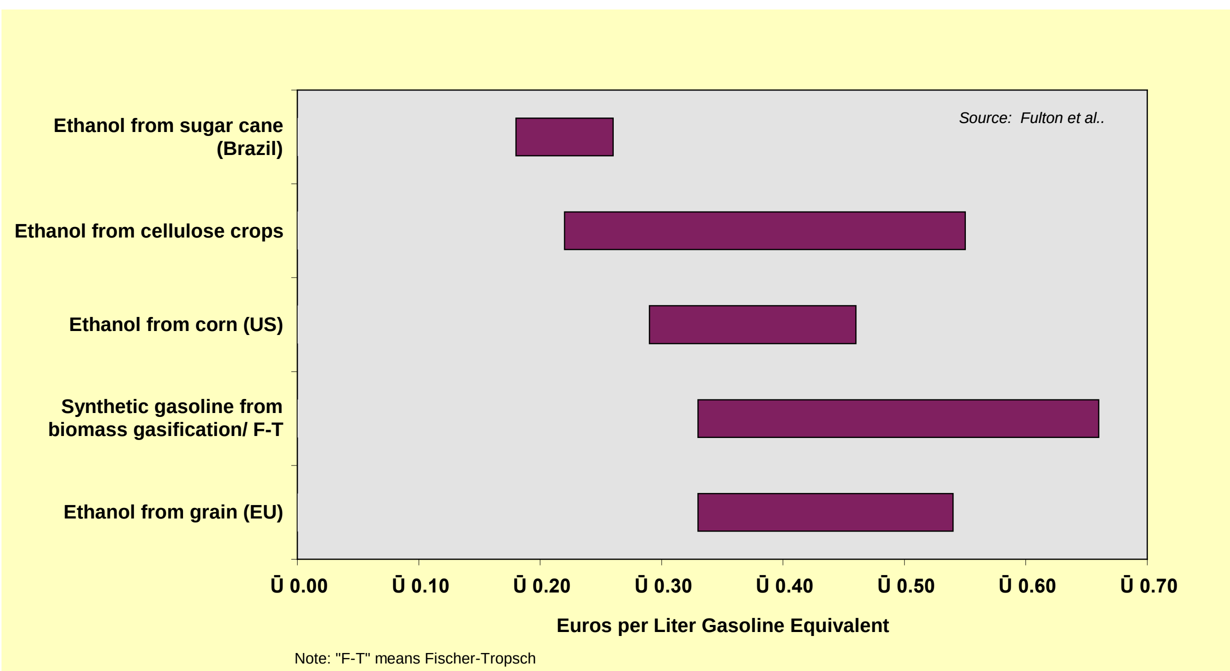
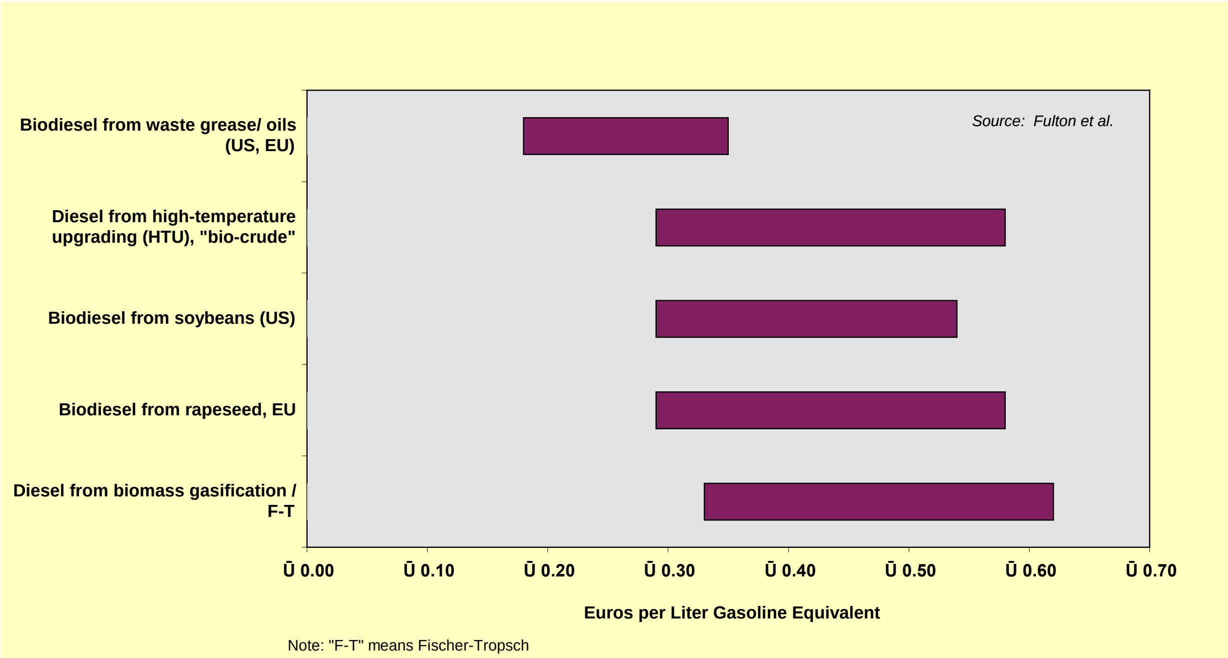


Figure 5–3. Cost Ranges for Biodiesel and Synthetic Diesel Production After 2010



5.4 Emerging Developments in Conversion Technology

While higher petroleum prices have improved the relative competitiveness of cellulosic refining procedures, advances in conversion technology are making cellulose more economical as well. The United States and the EU have been the primary laboratories for these advances, with the U.S. focusing more on the biochemical pathway and EU countries focusing more on the thermochemical pathway, particularly integrated gasification and F-T synthesis processes.

5.4.1 Biochemical Technologies

The United States has been the main driver of developments in biochemical conversion technologies. The U.S. Department of Energy (DOE), through its National Renewable Energy Laboratory, has funded efforts to develop cheaper enzymes that hydrolyze cellulose into sugar, which are called cellulases, and cheaper microorganisms that can ferment the unusual sugars in hemicellulose. DOE has given two companies, Novozymes and Genencor, the largest grants toward this end, though other enzyme suppliers (e.g., Iogen and Dyadic) have also been developing biotechnologies for this conversion pathway. As a result of proprietary advances, Novozymes announced in early 2005 that it had reduced the cost of enzymes to between €0.22–0.44 per liter ($0.10–0.20 per gallon), far less than the previous €1.09 per liter ($5 per gallon).[32]

Further developments that could reduce the cost of the biological pathway are also considered likely. The processing of lignocellulose consists of four biologically mediated events: production of cellulase, cellulase-mediated hydrolysis of cellulose, fermentation of six-carbon sugars (hexoses), and fermentation of five-carbon sugars (pentoses). These events can be carried out with varying degrees of consolidation, as follows:

- In *separate hydrolysis and fermentation* (SHF), each of these four events is carried out in a separate reactor mediated by a separate biological catalyst.

- In *simultaneous saccharification and fermentation* (SSF), hydrolysis and conventional fermentation are combined into one process step.

- Saccharification and conventional fermentation are combined with the fermentation of five-carbon sugars in *simultaneous saccharification and co-fermentation* (SSCF). SHF, SSF, and SSCF all feature a dedicated process step for cellulase production.

- In *consolidated bioprocessing* (CBP), all four biologically mediated events are combined into one process step, eliminating the need for dedicated cellulase production. CBP is widely regarded as the strategy offering the lowest cost in the long run. This kind of processing is, however, at a much earlier stage of development as compared to processes featuring dedicated cellulase production.[33]

A variety or processes have been shown to be effective at pre-treating lignocellulose, including processes based on exposure to dilute acid, steam, or hot water, ammonia, lime, and other agents. A variety of pretreatment processes are under investigation, with none having yet emerged as the process of choice, and each offering some advantages.[34] In North America, the Consortium for Applied Fundamentals and Innovation (CAFI) has been focusing on the pretreatment area in particular; here, several leading pretreatment experts are working collaboratively, led by Charles Wyman at Dartmouth University.[35]

In Europe, research on ethanol from cellulosic feedstocks is being conducted under a new EU-wide project "NILE," which covers a variety of conversion routes, and aims to build demonstration plants in 2007.[36]

It is estimated that for the biochemical pathway of hydrolyzing cellulosic biomass to ethanol the cost will be about €0.52 ($0.63) per liter for ethanol in the short term (the next 5–8 years); €0.31 ($0.37) per liter in the mid-term (8–12 years); and €0.21 ($0.25) per liter in the longer term (13–20 years).[37] (Note that these are costs per liter of ethanol, which has two-thirds as much energy per liter as gasoline.)

5.4.2 Thermochemical Technologies

Developments in the thermochemical pathway—i.e., gasification and F-T synthesis—have occurred primarily in Europe. In particular, Choren, a company financed by DaimlerChrysler, Volkswagen, and Royal Dutch Shell, has built a demonstration facility in Germany for converting wood wastes into synthetic diesel, which has operated successfully in Freiberg since mid-2003. The scale-up to a demonstration plant is now under way to further the technology to a pre-commercial state in the next three years.[38] The demonstration plant will have a capacity of 13,000 tonnes of biomass-to-liquid (BTL) per year, and will lay the base for construction of commercial-sized systems on the order of 200,000 tonnes/year. Besides the Choren system, other routes with different gasifier designs are being tested as well (e.g., by CUTEC), and European research is quite active in that field.[39] Market introduction of gasification/F-T schemes is expected in the next decade.

Pilot and demonstration units producing electricity via biomass gasification are now under development in Scandinavia, the United States, Brazil, and elsewhere in the EU, and both the

U.S. Department of Energy and the European Commission are actively involved in biomass power demonstration programs.[40]

Several opportunities exist for reducing the cost of the gasification conversion pathway through technological advances, including by consolidating gasification, gas cleaning, and/or gas processing (i.e. steam methane reforming and water gas shift) in a single vessel, and by developing large-scale, pressurized, oxygen-blown gasifiers.[41] Researchers in Europe and the United States are also seeking more-efficient catalysts and better methods of cleaning and preparing syngas for producing different products.[42] Gasifiers with self-contained gas cleaning have the potential to reduce capital costs by combining two unit operations. In order to produce co-products that can reduce the cost of fuels, researchers are also seeking markets for the many chemical byproducts of gasification and F-T synthesis.[43]

Meanwhile, gasification using not biomass, but fossil fuel feedstocks (primarily coal and petroleum) is already commercially established technology, for the production of both electricity and liquid fuels. In 2004, there are 117 such plants operating worldwide, which generated a variety of outputs, including chemicals (produced in 37 percent of plants), F-T liquids (36 percent), power (19 percent), and gaseous fuels (8 percent). An additional 38 plants with a combined synthesis capacity of more than 25,000 megawatts-thermal are planned to come online by 2010.[44] This existing infrastructure could be adapted to utilize biomass feedstocks as well.

It is estimated that for the thermochemical pathway using F-T technology for converting cellulosic biomass to synthetic diesel fuel the cost will be about €0.48 ($0.59) per liter for diesel in the short term (the next 5–10 years), and €0.29 ($0.35) per liter in the longer term (10–15 years). This analysis used the same methodology as that used in estimating the costs for ethanol via enzymatic hydrolysis (see section 5.4.1); after adjusting for the lower energy content per liter for ethanol compared to diesel, this analysis indicates that F-T technology may be able to produce biofuels at a cost roughly 20 percent lower than the enzymatic hydrolysis pathway in the long term (based on the cost per unit of biofuel energy produced). [45]

5.4.3 Pyrolysis

Other researchers have continued to develop pyrolysis pathways for producing biofuels, including new variations of "hydrous" pyrolysis that can process wet biomass without pre-drying. Royal Dutch Shell re-evaluated its hydrothermal upgrading process in the early 2000s and has since seen more promising results with this technology.[46]

Changing World Technologies, a company that has adapted a pyrolysis technology first developed during the 1980s, has built a facility in Philadelphia where it is experimenting with processing food wastes, sludges, offal, rubber, animal manure, black liquor, plastics, coal, PCBs, dioxins, and asphalt into pyrolysis oils, solids, and gases**.** It has also built a full-scale facility for processing turkey carcasses from a Cargill slaughterhouse in Carthage, Missouri. This has since been shut down, however, because nearby residents blamed it for producing odors.[47]

FZK in Germany introduced a decentral flash pyrolysis system to densify biomass for a more efficient transport to centralized gasification/FT-diesel plants, thus making direct use of the bio-oil for cogeneration, and the bio-coke would be transported as a feedstock to a larger-scale BTL plant. Currently, the design focuses on straw, but would also be suitable for other feedstock.[48]

5.4.4 Implementation

Of the two pathways for cellulosic conversion, the biochemical one appears to be closer to large-scale implementation. It requires less capital-intensive facilities and can be economical on a smaller scale.[49] Moreover, because it is part of the rapidly developing biotechnology sector, the costs of this pathway are likely decline faster than for other pathways, at least in the near- to mid-term, although not all experts agree on this.

Already, additional demonstration and commercial plants are being constructed that use advanced biological methods to refine ethanol from cellulose. In particular, the microorganisms that can ferment the five-carbon sugars in hemicellulose are ready for utilization. Iogen is already using recombinant *Zymomona mobilis* bacteria to produce ethanol at its facility in Ottawa, with wheat residue as the main feedstock, and is currently raising €290 million ($350 million) in capital to build a larger commercial facility in the United States or Canada.[50] In Nebraska, the Spanish company Abengoa plans to use the cheap enzymes developed by Novozyme to break down corn stover.[51] In Louisiana, BC International is building a facility that will combine conventional ethanol production with conversion of sugar cane residues, using the *E. coli* bacteria developed at the University of Florida.[52] And Colusa Biomass Energy Corp is marketing its process for converting rice hulls into ethanol. While most of these efforts are concentrated in the United States, SunOpta, Inc. plans to open the first commercial cellulosic ethanol plant in Spain in 2006, using technology from Abengoa.[53]

Although they are not as close to commercial success, gasification and F-T synthesis processes are progressing strongly as well. Gasification appears to be better able to accommodate a wide variety of feedstock than enzymatic processes, and (as noted earlier) permits the conversion of a greater fraction of feedstock carbon to liquid fuels. It also has the theoretical advantage of being able to process batches of different feedstock, and it can more easily be combined with coal gasification facilities.[54] Chinese planners have also shown interest in developing BTL technology, particularly by co-gasifying biomass with coal.[55]

Elsewhere, others are planning new pyrolysis biomass-conversion plants. Changing World Technologies aims to construct additional thermal depolymerization plants in Europe. And in Latvia and Ukraine, Rika Ltd. has licensed DynaMotive's "fast pyrolysis" technology and has leased 10,000 hectares to grow energy crops for this conversion.[56]

5.4.5 Transitioning Existing Biofuel Facilities into Cellulosic Refineries

There are several reasons to expect that cellulosic conversion facilities will initially be developed in an integrated manner with conventional biofuel production facilities. A key obstacle to advancing next-generation conversion technologies has been the expense of harvesting and collecting the biomass feedstock. Existing biofuel production facilities, however, already process large amounts of biomass. The high-fiber byproducts of starch-based ethanol production processes—such as dried distillers grains (DDG)—are a pre-collected source of cellulosic mass. At sugar-based conversion facilities, bagasse and beet pulp are convenient sources of cellulose. With this convenient feedstock nearby, existing facilities are in a position to experiment with pilot plants that convert only a share of this cellulosic mass into fuels.

Previous models for producing liquid fuels from lignocellulosic matter assumed that both cellulose and hemicellulose would have to be utilized; otherwise, the expense of harvesting and collecting the feedstock would be too great. However, the availability of large quantities of low-value cellulosic biomass at integrated facilities could make it economical to convert the biomass into liquid fuel. Thus, existing conversion facilities could be a nursery for the evolution of cellulosic refineries.[57]

5.5 "Mature" Applications of Cellulosic Conversion Technologies

The technologies for converting biomass into liquid fuels are developing along many different routes, and some are more viable today than others. As they mature, however, the requirements of specific applications will influence which technologies are most appropriate; it is also possible that combinations of several conversion technologies will be used to address the requirements of particular feedstock or application.

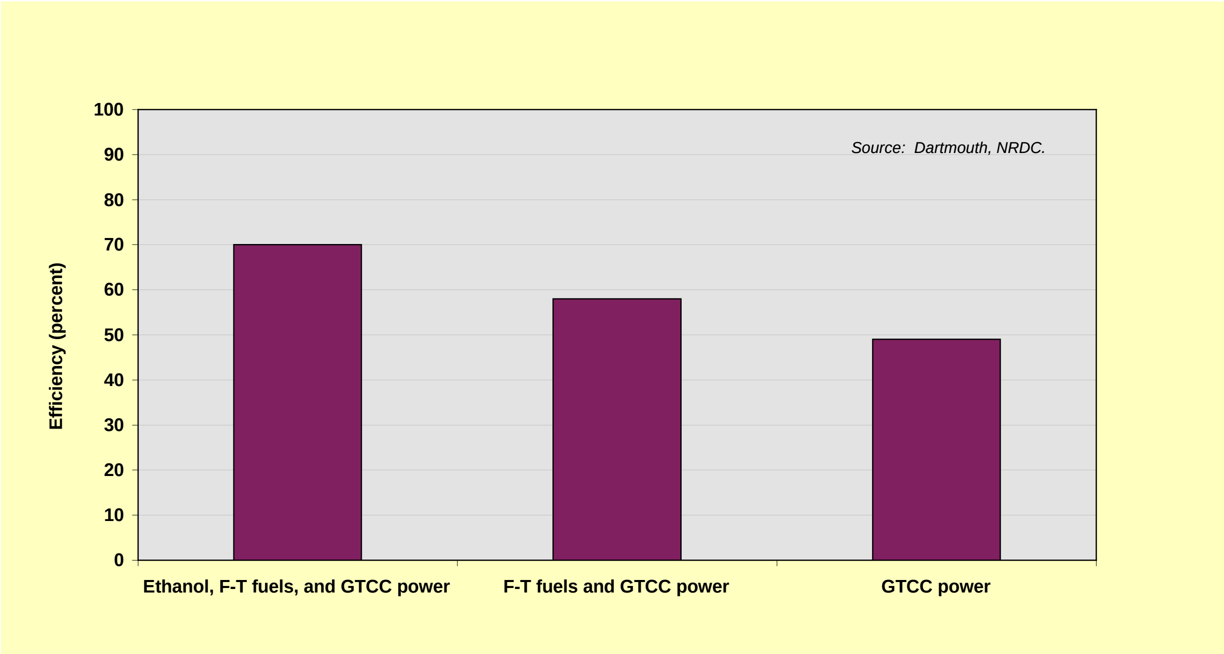
For example, woody feedstock, including municipal solid waste, is probably more suitable for gasification and F-T synthesis because it contains relatively more lignin, which biological processing cannot convert. Compared to grassy feedstock, woody feedstock also contains less chlorine and alkali metals, which can foul up gasification operations. Grassy feedstock, including agricultural residues, is thus more suitable for the biological pathway, because it contains less lignin. And hydrous pyrolysis is likely to remain a good solution for producing liquid fuels out of wet organic waste.

These processes could also work in tandem on the same feedstock. For example, pyrolysis has recently been considered a way to aggregate wet biomass and extract some pyrolysis oil on a smaller scale, before sending the residual solids to a larger-scale gasification facility.[58]

The gasification pathway could also process the residual lignin left over after the cellulose and hemicellulose fractions of a feedstock are processed biologically. One detailed analysis of different conversion pathways concluded that this combination was the most economical and energetically efficient, as well as the most effective means for displacing petroleum, because it converts the lignin into liquid as well.[59] (Though some analyses have found that gasification facilities will need to be larger than biological facilities, rather than smaller and secondary.) In this idealized scenario, ethanol would be produced through biological conversion of the feedstock's carbohydrate fraction. Then, the lignin-rich residue resulting from this bioprocessing, as well as the methane-rich biogas from wastewater treatment, would be thermochemically processed into F-T diesel and gasoline. This would result in very little waste (and energy loss), and permit a small amount of power export to the electricity grid. (See Appendix A–4 for a schematic diagram of this process.) Figure 5–4 provides a comparison of its energy efficiency.[60])

The results of the analysis indicate that such mature biomass refineries can potentially produce fuels at costs competitive with gasoline. The ethanol + F-T fuels + power scenario, for example, produces ethanol at €0.14 per liter, or €0.20 per liter of gasoline equivalent ($0.93 per gallon[61]) and F-T diesel at €0.22 per liter ($1.04 per gallon), at a production scale of 5,500 dry tonnes feedstock/day. It also entails a 12 percent internal rate of return (IRR), 60 percent equity financing, and electricity valued at €0.03 ($0.04) per kilowatt-hour. This scenario was most profitable at prices above roughly €6 ($7.3) per gigajoule of gasoline equivalent (€0.19 per liter/$0.89 per gallon wholesale), or about €21 per barrel ($25) of crude oil. Below this price, dedicated power production was the most profitable configuration, achieving an IRR of just under 10 percent.

Figure 5–4. Processing Efficiency for Three Biorefining Scenarios



5.6 The Biorefinery Concept

An oft-touted model for future biofuel production will be a kind of "biorefinery" where both fuels and co-product materials are produced. This model would mimic petroleum refineries where fuels are produced simultaneously with chemicals and materials. In the past, conventional fuel production has been a stepping-stone on the way to chemical production, as occurred with the petrochemical industry in the 1940s and with gasification-based coal processing in South Africa during the 1980s; similarly, commercial production of organic chemicals from biomass has been suggested as a stepping-stone to commercial production of biofuels.[62]

Notwithstanding anticipated synergies between the production of chemicals and energy (fuel, power) from biomass, one complicating factor is the size of markets for organic chemicals, which tend to be relatively small compared to markets for liquid fuels. This will create a challenge in identifying chemical co-products for biorefinery production that will not exceed the market demand, as large quantities of liquid fuels are produced at these facilities.

Typically, fuels would represent the bulk of total biorefinery production, while chemicals and other materials would generate the bulk of the profits. This is similar to the situation with conventional fuels, where the flow of energy leaving the U.S. oil refining industry as liquid fuels is more than 25-fold greater than the flow leaving as petrochemicals. Chemical production makes a disproportionately large contribution to the profitability of oil refining and lowers the price of fuels because of its higher profit margins relative to fuel production; fuel production, meanwhile, lowers the price of chemicals by providing economies of scale.[63]

Biochemical conversion pathways may offer a more likely option for co-producing bio-based materials, particularly since the lignin fraction of the biomass feedstock is not converted to ethanol fuel in the conversion process. Although bio-based chemicals are currently "specialty" chemicals produced in separate facilities, they could instead be economical co-products of biorefineries. Already, one conventional "wet" mill for corn-ethanol in the U.S. state of Nebraska generates a range of co-products, including high fructose corn syrup, high-protein animal feedstock, and specialty chemicals like polylactic acid (a feedstock for corn-based plastics and fabrics).[64]

Even though most bio-based products are made via the biological pathway, gasification and F-T synthesis also has the potential to co-produce a wide range of materials. F-T synthesis could theoretically produce all the hydrocarbons produced by petroleum refineries, though the economics are unlikely to be the same for all products.

Future biorefineries will benefit from their ability to mimic the energy efficiency of modern oil refining as well. A key aspect of this refinery approach is extensive heat integration, whereby the heat available from some unit operations can be used to meet heat requirements of other operations within the process. Integrating heat flows in the most beneficial manner within a refinery with multiple heat sources and heat sinks is referred to as "pinch analysis," and is routinely employed in designing and upgrading oil refineries. Without heat integration, which allows heat to be reused multiple times, auxiliary energy inputs to the process would be much higher and the efficiency would be lower.[65]

5.7 Near-Term Prospects for Cellulosic Liquid Fuels

Despite their promise, cellulosic conversion technologies are still probably at least 8–15 years away from supplying a significant proportion of the world's liquid fuels. Biochemical pathways appear likely to begin significant commercial expansion in the next 8–10 years, and thermochemical F-T pathways are expected to begin such expansion in the next 10–15 years. This will depend partly on the amount and quality of research and development funding that governments provide over this period; in particular, researchers will need to continue reducing the cost of producing valuable enzymes and cleaning F-T gasifiers and syngas.

The promise of cellulosic biofuels will also hinge in great part on how much support governments provide to help risk-averse investors build a large number of cellulosic-conversion plants.[66] The cost and risk of building new conversion facilities is currently hampering development of these next-generation fuels. Building a new cellulosic biofuel plant requires a larger capital expenditure than building a conventional biofuel production plant, and investors are not assured that the price of petroleum will remain high enough for these operations to remain competitive.

In the future, cellulosic fuels could be cheaper than petroleum fuels, should the latter prices remain high, but they are still likely to be more expensive than conventional first-generation biofuel conversion technologies for some time.

Moreover, even though the technologies appear to be approaching viability, it will take a long time for their application to ramp up to a level that can compare to the current petroleum-fuel infrastructure. Even with a dedicated effort to expand the production of cellulosic-based fuels, it will likely be decades before these substantially rival petroleum fuels. Still, cellulosic fuels have great promise, and in the medium term, they could begin to provide a growing share of the global fuel supply.

5.8 Conclusion

The technologies for converting lignocellulosic matter into biofuels exist and are becoming increasingly cost-competitive as the technologies advance. Various analyses support the conclusion that mature conversion technology will be able to produce fuels from cellulosic biomass with high process efficiency and competitive costs—though ultimately, the features of mature biomass conversion technology will be known only after such technology has been developed and widely commercialized. Moreover, the economic competitiveness of these fuels, and the development of the conversion pathways, will depend substantially on the relative price of petroleum in the future.

The pathways for advancing today's evolving lignocellulosic conversion technology to maturity will need to be shaped by a clear vision of where we can expect this road to lead. Both technicians and policymakers should continue to clarify which efforts at converting biomass into fuels will be most productive. Strategies to do this can be roughly categorized as falling into support for pre-commercial R&D, and support for commercialization per se. A combination of these approaches appears to be considerably more promising than doing either alone. Although a detailed commentary on R&D policy is outside the scope of this chapter, in general most countries are underinvested in breakthrough-targeted R&D and applied fundamentals as compared to other activities.

Efficient and lower-cost biomass conversion processes are necessary but not sufficient conditions for biomass to make a large contribution to providing energy services (e.g. heat, mobility, light, work). Societies will also need to be willing to invest in developing these technologies. As has been the experience with other promising renewable energy technologies, a period of development and governmental support is necessary to push them over the threshold into economical viability.

Since these conversion technologies are on the verge of viability, continued research and development could be helpful, but extensive deployment is perhaps more important. This will allow operators to streamline new facilities while also reducing the risk perceived by investors looking at an "unproven" technology. Governments should thus offer supports such as loan guarantees and guaranteed markets for new cellulosic biofuel production facilities today, while also pursuing a vision of more integrated and efficient conversion processes in the future.

Chapter 6. Long-Term Biofuel Production Potentials

6.1 Introduction

In the future, it may be possible to supply a substantial share of the world's energy needs using cellulosic biomass resources. But exactly how much remains uncertain. Estimates of the planet's biomass production potential vary considerably: in a highly optimistic scenario, biomass energy could well exceed total world energy requirements; in the most pessimistic scenario, it could provide few if any additional contributions.

Bioenergy is useful not only as a source of liquid transportation fuel, but also to meet energy needs in a wide range of other applications, including heat and power and the production of bio-based products such as construction materials, clothing, and plastics. These different uses will likely combine to increase the harvesting of biomass residues and dedicated energy crops. In some cases, with more limited supplies of biomass, these different uses will compete. When production is more abundant, co-harvesting and biorefineries may permit lower-cost biofuels.

This chapter explores the potential contribution of cellulosic biomass in meeting future world energy needs. In particular, it rests on work done to consider various scenarios in which different levels of biomass energy can be sustainably harvested. Among the most significant variables in determining the future of biomass energy are the ability of agronomists to boost the food and feed yields of conventional crops and their ability to increase the biomass produced by dedicated energy crops. Humanity's collective demand for food and land is equally significant. Competing uses for land and biomass, as well as how we respond to climate change and ecological limitations, will also determine the quantity of biomass energy available for use as biofuels.

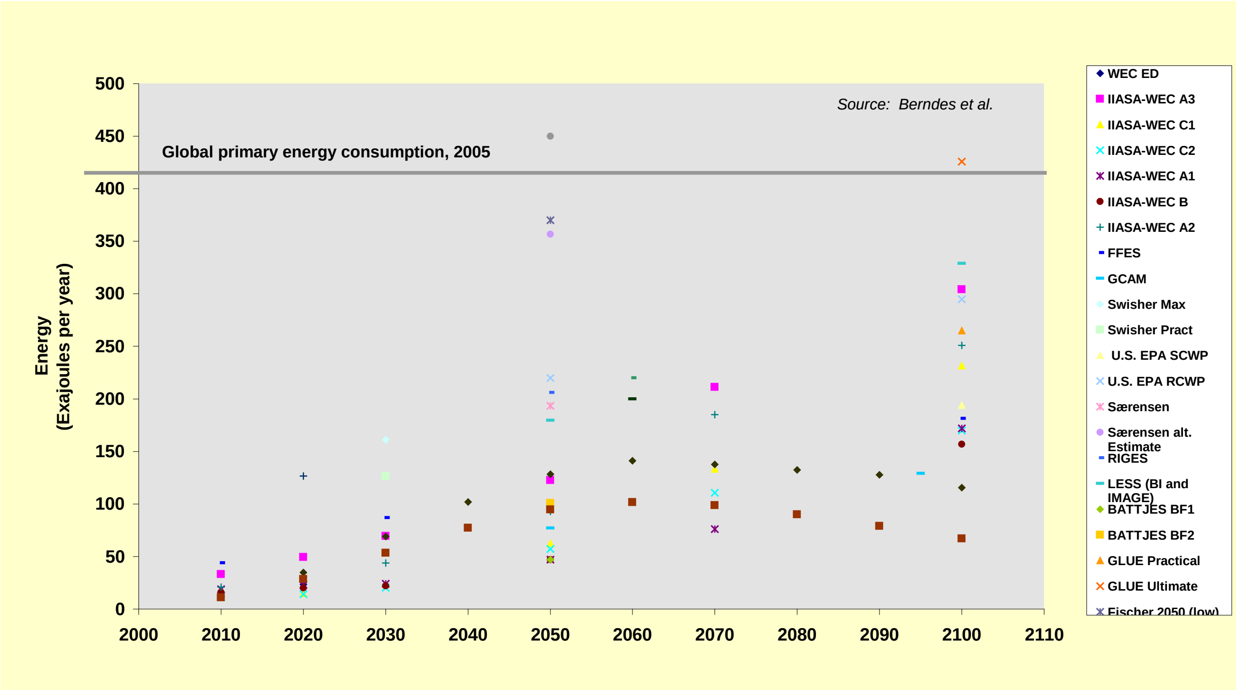
6.2 Bioenergy in the World Energy Mix

Currently, the world consumes roughly 430 exajoules (EJ) of energy per year. Of this, approximately 100 EJ—23 percent—is used to meet transportation needs. Although it proves difficult to account for all uses of biomass resources in all regions, bio-based energy is estimated to account for roughly 9 percent of the world's total energy, or nearly 40 EJ.[1]

Yet bioenergy's potential is enormous. Studies suggest that biomass could potentially supply anywhere between 0 EJ to more than 1,000 EJ of energy by the year 2050. In the most optimistic scenarios, bioenergy could provide for more than two times the current global energy demand, without competing with food production, forest protection efforts, and biodiversity. In the least favorable scenarios however, bioenergy could supply only a fraction of current energy use, perhaps even less than it provides today.[2]

Figure 6–1 illustrates the results from 13 studies that have evaluated the potential to harvest energy from biomass.[3] Note that these studies have been mostly "top-down" evaluations, derived from the anticipated demand for biomass or from extrapolations of the current supply. The present report, however, relies primarily on a more "bottom-up" analysis, which models different scenarios, and, importantly, considers the prospects for increasing the yields of both food and energy crops.

Figure 6–1. A Review of 13 Studies on Biomass Potential, 2010–2100



Potential sources of biomass energy include energy crops grown on existing agricultural or marginal lands, agricultural residues, organic wastes, and forest residues. (See Chapter 4.) Table 6–1 provides an overview of the potential contribution of each of these biomass types to the global energy supply, to 2050.[4] Each of these categories is discussed in further detail in later sections of this chapter.

The potential for biomass to meet a substantial share of future transportation energy needs depends on several key factors. They include:

- *Developments in agronomy.* If farmers are able to increase their agricultural efficiencies significantly, they could not only produce more crop residue per hectare, but they may be able to free up prime agricultural land for the harvesting of dedicated energy crops. If plant breeders are able to develop highly productive energy crops that also grow on marginal lands, these crops could theoretically yield vast new quantities of biomass resources. Foresters might also increase forest yields. (See Chapter 4.)

- *The size of the human population and its collective appetite for food and land area.* If our ability to boost food crop yields per hectare continues to rise (for example, through advanced biotechnology and crop breeding improvements), some analysts surmise that humanity may be able to feed itself with less land than we use today—thus freeing up land for energy crop production. Food and related land requirements will also depend on the level of demand for more calorie-intensive meat and dairy products, as well as on the rate of urbanization, which threatens to pave over or subdivide lands otherwise available for biomass cultivation.

Table 6–1. Bioenergy Production Potentials for Selected Biomass Types, 2050

Biomass Type	Bioenergy Potential (exajoules)	Main Assumptions and Remarks
Agricultural Residues	15–70	• Based on estimates from various studies. • Potential depends on yield/product ratios, total agricultural land area, type of production system. Extensive production systems require leaving of residues to maintain soil fertility; intensive systems allow for higher rates of residue energy use.
Organic Wastes	5–50+[b]	• Based on estimates from various studies. • Includes organic fraction of MSW and waste wood. • Strongly dependent on economic development and consumption, and as well as use for biomaterials. • Higher values possible by more intensive biomaterials use.
Dung	5–55 (or possibly 0)	• Use of dried dung. • Low range value based on current global use; high value reflects technical potential. • Utilization (collection) over longer term is uncertain.
Forest Residues	30–150 (or possibly 0)	• Figures include processing residues. • Part is natural forest (reserves). • Sustainable energy potential of world forests unclear. • Low value based on sustainable management; high value reflects technical potential.
Energy Crop Farming (current agricultural lands)	0–700 (100–300 is more average)	• Potential land availability of 0–4 global hectares (Gha), though 1–2 is more average. • Based on productivity of 8–12 dry tonne/ha/yr[a] (higher yields are likely with better soil quality). • If adaptation of intensive agricultural production is not feasible, bioenergy supply could be zero.
Energy Crop Farming (marginal lands)	60–150 (or possibly 0)	• Potential maximum land area of 1.7 Gha. • Low productivity is 2–5 dry tonne/ha/yr.[a] • Bioenergy supply could be low or zero due to poor economics or competition with food production.
Biomaterials	Minus 40–150 (or possibly 0)	• Provide an additional *claim* on biomass supplies. • Land area required to meet additional global demand is 0.2–0.8 Gha • Average productivity is 5 dry tonnes/ha/yr[a] • Supply would come from energy crop farming if forests are unable to meet this demand.
Total	**40–1,100 (250 –500 is more average)**	• Pessimistic scenario assumes no land for energy farming, only use of residues; optimistic scenario assumes intensive agriculture on better soils. • More average range = most realistic in a world aiming for large-scale bioenergy use.

Notes: (a) heating value: 19 GJ/tonne dry matter; (b) the energy supply of biomaterials ending up as waste can vary between 20–55 EJ (or 1,100-2,900 million tonnes of dry matter per year). Biomass lost during conversion, such as charcoal, is logically excluded from this range. This range excludes cascading and does not take into account the time delay between production of the material and its 'release' as (organic) waste. Source: See Endnote 4 for this chapter.

- *Energy conversion technologies.* Harvesting, processing, and using this bioenergy more efficiently will reduce the need for additional acreage or higher yields. New technologies are making it possible to efficiently produce liquid transportation fuel from cellulosic biomass. Even if this conversion should prove comparably inefficient, however, it will likely raise the economic potential for producing biomass, by adding demand from the transportation energy sector.

These and other key elements determining bioenergy potential are laid out schematically in Appendix A–5 at the end of this report.

6.3 Biomass Residues and Organic Wastes

As discussed in Chapter 4, vast amounts of biomass residue exist that could potentially be used as feedstock for biofuel production. Much of the plant matter produced by common crops is left on the fields after harvest, and a large portion of this decomposes into carbon dioxide rather than returning to the soil. Similarly, forestry practices leave behind large quantities of unharvested wood, and fire mitigation practices have allowed forest underbrush to accumulate. Of the biomass that is already being harvested, large amounts of residues are generated at agricultural processing facilities and forestry mills, including sugar cane bagasse, rice hulls, nut shells, saw dust, and black liquor (at paper mills). In urban areas, cellulosic residues include portions of municipal solid waste, grass clippings, and wood from tree trimmings and land clearing activities.

Studies of biomass potential estimate that together, these residues and organic wastes could supply between 40 and 170 EJ of energy per year on a global basis. Although additional energy would be required to process the biomass into liquid fuels, this range of potential biomass energy is roughly comparable to the 100 EJ used worldwide to meet transportation needs today. Achieving the high end of the range would require boosting the productivity of crops and forests (to increase residue availability) and developing economical ways to simultaneously harvest conventional food crops and crop residues, as well as timber and forest residues.[5]

Residues and wastes have several advantages over dedicated energy crops. Most of them would require no additional land acreage, as they are typically pre-collected into piles at large agricultural and forestry facilities and often represent "waste" that must otherwise be disposed of. As a result, this feedstock is cheaper and is likely to be the first source of biomass to be tapped. Already, the wood products industry uses most lumber residues and much of the forestry residue in Europe and the United States for processing purposes and to generate co-products such as wood chips, fiberboard, etc.[6]

For sustainability reasons, however, estimates of potential bioenergy from waste and residues would likely be lower than those suggested above. In general, it is a good idea to retain some portion of biomass residue in the field or forest to hold carbon, water, and other nutrients in the soil, and to provide habitat for various species. Leaving a protective amount of residue behind is especially important on steep slopes or on ecologically sensitive sites that have particularly erodible soils, or are near riparian areas.[7]

Even taking these considerations into account, studies suggest that large quantities of residue and waste biomass would still be available for harvesting. One study exploring the biomass potential in the United States found that harvesting residues from agriculture and forestry alone could provide more than 700 million tonnes of biomass annually, or enough energy to displace more than 20 percent of the country's current petroleum fuel use.[8] Global estimates of this potential energy have ranged from 15 EJ to more than 200 EJ.[9]

6.3.1 Agricultural Residues

The production potential for agricultural residues depends on the various yields of different agricultural products, the total agricultural land area, and the type of production system. Less-intensive management systems require the reuse of residues for maintaining soil fertility, reducing the total amount that can be sustainably removed. More intensively managed systems, meanwhile, allow for higher use-rates of residues but also typically rely on crops with lower crop-to-residue ratios, such as corn.[10]

Estimates of the energy potentially supplied by agricultural residues vary from around 15–70 EJ per year. The latter figure is based on the regional production of food multiplied by the co-production of residue and the amount of residue that can be sustainably harvested.[11] These figures do not subtract potential alternative uses for agricultural residues. Hall et al. (1993) estimate that just by harvesting residues from the world's major agricultural crops (e.g. wheat, rice, corn, barley, and sugar cane), a 25 percent recovery rate could generate 38 EJ of bioenergy.[12] Worldwide, large stores of rice hulls, coconut husks, and sugar cane bagasse currently exist, and in some instances this is already used to provide a local source of power.[13] (See Table 6–2.)

Table 6–2. Annual Bagasse Availability in the Top 10 Sugar Cane Producing Countries

Country	Bagasse Availability (million tonnes)	Potential Bioenergy (exajoules)
Brazil	67.3	0.521
India	56.8	0.439
China	28.0	0.216
Australia	18.0	0.139
Thailand	17.8	0.138
Mexico	16.4	0.127
Cuba	12.6	0.098
United States	12.2	0.095
Pakistan	12.1	0.093
South Africa	8.3	0.064

Note: Assumes a yield of 3.26 tonnes of fuel bagasse per tonne of cane sugar produced, at 50 percent humidity.)
Source: See Endnote 13 for this chapter.

6.3.2 Organic Wastes

Organic wastes, such as the organic fraction of municipal solid waste (MSW) and waste wood (e.g., demolition wood), are a particularly attractive source of biomass energy because they can have a “negative” price. In other words, collecting and utilizing these can result in savings from landfill tipping fees.[14]

Estimates of the bioenergy potential of wastes depend strongly on assumptions about economic development, consumption, and the use of biomaterials; nevertheless, the ranges projected for MSW in the longer term (beyond 2040) are between 5 EJ and 50 EJ. (Higher values are possible when biomaterials are more intensively used and then made available for recycling.) Translated into biofuel production, a city of 1 million people could theoretically provide enough feedstock to produce about 430,000 liters of ethanol per day.[15] (See Sidebar 6–1).

Sidebar 6–1. How Much Ethanol Could the Municipal Solid Waste from a City With One Million People Produce

The average person in the United States generates approximately 1.8 kilograms of municipal solid waste (MSW) per day. This typically contains about 75 percent of mostly cellulosic organic material, including waste paper, wood wastes, cardboard, and waste food scraps. Thus, a city with 1 million people produces around 1,800 tonnes of MSW in total, or about 1,300 tonnes per day of organic material.

With technology that could convert organic waste to ethanol, roughly 330 liters of ethanol could be produced per tonne of organic waste. Thus, 1,300 tonnes per day of organic waste from a city with 1 million people would be enough feedstock to produce about 430,000 liters of ethanol per day, or approximately 150 million liters per year. This is enough fuel to meet the needs of more than 58,000 people in the United States; 360,000 people in France; or nearly 2.6 million people in China at current rates of per capita fuel use.

Source: See Endnote 15 for this chapter.

Animal excrement, too, could supply a significant amount of bioenergy, perhaps between 5 EJ and 50 EJ per year. Yet even more so than crop residues, it is valuable for improving and fertilizing soils. It can also be harder to recover and can cause health problems among those who work with it.[16]

6.3.3 Forest Residues

The sustainable energy potential of the world’s forests is also uncertain. However, a recent evaluation of forest reserves and trends in global wood demand concluded that even the highest projected demand for wood products could be met without further deforestation, suggesting that forest residues can be an ecologically benign feedstock for energy production.[17]

In terms of potential bioenergy provision, studies show that forest residues can contribute between 30 EJ and 150 EJ per year in 2050. The most promising producer regions are Latin America and the Caribbean, the former Soviet Union, and to some extent North America. Key variables include the demand for industrial roundwood and fuel wood (obtained both legally and illegally), plantation establishment rates, natural forest growth, and the impact of technology and recycling.[18]

Despite this potential, the amount of energy that can be obtained from forest residues and other waste biomass resources will be limited in comparison to energy crops; moreover, these reserves will likely be depleted first as demand for bioenergy grows. Finland, which has focused on harnessing biomass energy for many years, has already used all of its accessible residues and wastes and is now importing wood energy.[19]

6.4 Energy Crops and Land Availability

Energy crops, bred and cultivated to produce the maximum amount of biomass energy per hectare, hold the greatest promise for increasing the availability of bioenergy. As discussed in Chapter 4, fast-growing grasses and trees cultivated on plantations can be highly productive. They can grow on pastureland, degraded land, and lands otherwise considered undesirable for agriculture. Agronomists could potentially increase energy crop yields by twice or more.[20]

Depending on yield improvements and the quality of land available for their production, high-yielding energy crops could provide the bulk of future bioenergy supplies, ranging from 0 to 850 EJ per year (for farming on current agricultural as well as marginal lands). At the high end, this would represent as much as twice the current global energy use (430 EJ) and about eight times current transportation energy use (100 EJ).[21] At the low end, increased demand for food, coupled with the failure to increase agricultural efficiencies quickly enough, could eliminate the availability of even marginal lands for energy production. It is also likely that harvesting bioenergy crops on particularly unproductive lands will prove uneconomical.

6.4.1 Growing Energy Crops on Marginal Lands

So-called “marginal” lands cover an estimated 1–3 billion hectares, or about 7–20 percent of Earth’s land surface.[22] They may be considered undesirable for agriculture for a variety of reasons, including high acidity; salinity; high levels of phosphorus, aluminium, or ferric oxides; poor drainage; erodability; shallowness; or tendency to expand and contract.[23] In many cases, land that was once highly productive has been made marginal by over-harvesting or over-grazing.[24]

Studies estimate that the marginal land area available for cultivating energy crops is between 100 million and 1 billion hectares.[25] The remainder lacks sufficient water or soil quality to be economical for energy crop harvesting. Other sites, such as farmland set aside to protect water quality, may have yields equivalent to those possible on high-quality agricultural land. The range of these yields will depend on the price of biomass and the ability of agronomists to develop crops particularly suited to specific conditions.

Cultivating energy crops on marginal lands could be either detrimental or beneficial to these areas, depending on what the crops replace and how they are managed. For instance, if energy crops replace more varied ecosystems with monocultures or are grown using fertilizers and pesticides, these practices could cause damage to biodiversity or ecological systems. Large-scale expansion of energy crop production would also lead to an increase in water use for irrigation, which in some countries would further strain stressed water resources. Issues of water supply and demand need to be better incorporated into future assessments of bioenergy potentials.[26]

At the same time, energy crops could be a means of restoring degraded lands, improving soil quality, and restoring water cycles in regions affected by desertification. Virtually all of the promising new energy crops are perennials, with roots that hold soil in place year-round. Such crops could be planted as part of efforts to protect riparian areas or reduce erosion. Energy cropping could also serve as an ecological intermediary between dedicated agricultural land and dedicated conservation land.[27] (For more on the environmental risks and benefits associated with energy crop cultivation, see Chapter 12.)

6.4.2 Growing Energy Crops on Agricultural Land

The greatest theoretical potential for producing bioenergy lies on land that is useful for agriculture as well. Like conventional food and feed crops, energy crops grow best on prime farmland. While some analysts assume that the growing human demand for food will require the use of all available cropland, this is not necessarily the case. Whether and how much agricultural land could be made available for energy cultivation is a central uncertainty in the future of next-generation biofuels. (See Chapter 8 for a discussion of "food vs. fuel.")

Many assessments of biomass potential have failed to consider the extent to which increasing agricultural efficiencies could contribute to bioenergy production. Agricultural yields per hectare have been improving by around 1–2 percent annually for decades, and the meat industry has increased yields even faster by feeding cattle with grains, such as soybeans, rather than wild grasses.[28] So far, agriculture's ability to outpace population growth and the demand for food has led to regional overproduction, one of the primary reasons governments have launched conventional biofuel programs to begin with. (See Chapter 1.) Although the increase in yields is expected to slow, many experts still expect output to keep rising, particularly with wider use of hybrid crops, chemical inputs, irrigation, and mechanization.[29]

Unfortunately, many of the key ways to improve agricultural efficiency can also be socially and environmentally destructive. Growing crops where they are most productive can lead to monocultures and the loss of genetic and biological diversity. Mechanization can reduce the employment opportunities in rural communities. The use of fertilizers and pesticides can contaminate soils and waterways. Transitioning from pastures to feedlots can be unhealthy for the animals. And genetically modified organisms represent a new degree of tampering with both genes and ecosystems. Nonetheless, such techniques are often critical for improving the efficiency of human land use, and may be essential if the goal is to increase agricultural output per hectare of land.[30]

Improving Yields in Sub-Saharan Africa

The opportunity for increasing agricultural efficiencies is greatest in developing countries, where yields can be ten times lower than those on comparable land in industrialized countries.[31] African countries stand out for their potential to improve land productivity. Mozambique, for example, has abundant rainfall and fertile soils, but the small-scale, low-input nature of its agriculture has typically meant lower yields. Average cereal yields in the country are just 1 tonne per hectare, well below the 8–12 tonnes per hectare yields attainable in high-input agricultural systems in industrialized countries.[32] Batidzirai et al. (2006) estimate that farmers in Mozambique could increase their productivity by seven times with just moderate use of agricultural technologies, such as fertilizers, pesticides, selected seeds, and large-scale harvesting practices. Similar yield increases are potential elsewhere in Africa as well.[33] (See Table 6–3.)

Table 6–3. Potential Yield Increases by 2050 for Four Agricultural Scenarios

Region	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	(factor of increase, 1998 = 1)			
North America	1.6	2.3	2.3	3.2
Oceania	2.4	3.7	3.7	4.6
Japan	2.7	2.8	2.4	3.0
West Europe	0.9	1.5	1.3	1.9
East Europe	2.1	3.3	3.3	4.1
Former Soviet Union and Baltic States	3.2	5.4	5.3	6.7
Sub-Saharan Africa	5.6	6.2	6.2	7.7
Caribbean & Latin America	2.8	3.6	3.5	4.5
Middle East & North Africa	1.4	2.3	2.3	2.9
East Asia	2.3	2.7	2.5	3.2
South Asia	3.7	4.5	4.5	5.6
World	**2.9**	**3.6**	**3.6**	**4.6**

Note: Table shows potential increase in crop yields from 1998 to 2050, based on the average for all crops analyzed. Scenarios 1–4 represent four different but relatively optimistic possibilities: Scenario 4 assumes that animals do not use grazing land and utilize grain foods efficiently, while crops are irrigated and have "extremely" high yields; Scenarios 2 and 3 assume that crops are irrigated but have only "very high" yields, and Scenario 2 assumes that some meat will be raised via grazing. System 1 also assumes some animal grazing and "very high" yields, but no irrigation. Source: See Endnote 33 for this chapter.

Implementing more efficient agricultural practices across sub-Saharan Africa could free up as much as 700 million hectares of surplus agricultural land. By planting highly productive plantations of eucalyptus and other energy crops on this land, sub-Saharan Africans could harvest as much as 347 EJ of bioenergy.[34]

It should be noted that both local agencies and international development organizations have sought to improve agricultural yields in Africa for decades; however, due in large part to continuing poverty, these efforts have met with only limited success.[35] Moreover, unless such agricultural changes are managed carefully, they could cause considerable social and ecological disruption. Nevertheless, by generating additional revenue for rural communities, bioenergy crops could theoretically help to improve conventional agricultural yields by enabling greater investment in agricultural technologies. Since capital and investments in infrastructure are critical to improving agricultural yields, such schemes warrant further analysis.[36] (See Chapter 8 for more on the benefits of biofuel production for rural communities.)

Improving Yields in Central and Eastern Europe

There are also opportunities for improving agricultural efficiencies in Central and Eastern Europe. Following the collapse of the Soviet Union, the farm acreage in many of these historically agricultural countries—including Ukraine, Poland, and Romania—declined. Most of these countries also continue to use agricultural practices that are inefficient compared to those in Western Europe. As these countries enter the European Union and adopt the EU's Common Agricultural Policy, efficiency levels are likely to improve, leading to greater mechanization and use of inputs, and higher yields. Bioenergy crops may provide a new market for European farmers displaced by this transition.[37]

Shrinking Grazing Lands

Grazing lands are considered key sites for future bioenergy crops. Studies suggest that transitioning livestock from pastures to more-concentrated feedlots could free up many hectares of semi-agricultural and marginal land, either for production of energy grasses or partial conversion to woodlands.[38] However, such shifts are controversial. Confining animals in smaller areas can increase the risk of both animal and human disease, create enormous pollution issues, and be unhealthy for the animals.[39] It also entails using a larger share of human food crops for animal feed. On the other hand, the transition from grazing land to perennial energy crop cultivation could permit the restoration of healthier grassland ecosystems. (See Chapter 12.)

Rising Human Demand for Food

To free up agricultural land for the cultivation of energy crops, agricultural efficiency will need to rise faster than the human appetite for food. Population growth is the most significant driver behind increased food demand. While human numbers are expected to stabilize by mid-century, the United Nations "medium-range" forecast still puts world population at around 8.9 billion people in 2050, up from 6.5 billion in early 2006.[40] Over the next three decades, food demand is projected to increase by 1.5 percent per year—with 1 percent of this annual growth due to continued population increase, according to the U.N. Food and Agriculture Organization.[41]

The rest of the growth in projected food demand comes from changes in diet, as more of the world's people are able to afford calorie-intensive meat and dairy products. Producing these items can require large resource inputs, including additional land to grow crops for animal feed.[42]

All of the scenarios presented in this chapter have accounted for the increasing human demand for food, considering both the forecasted size of the global population and the expected dietary preference for meat.

Climate Change

Projected climatic changes in the decades to come only add to the uncertainty about humanity's potential to boost agricultural yields. Shifts in the hydrological cycle may cause droughts in some areas, while bringing excessive or unseasonal rains to others. Temperature increases could eventually shift bands of vegetative growth away from the Equator, requiring regional adaptations in agricultural practices. Some areas might even benefit as increased levels of carbon dioxide stimulate faster plant growth: Canada's plains, in particular, could benefit from longer growing seasons and more plentiful rain. However, other regions, e.g. in southern Europe or Africa, would likely suffer.

In tropical areas in particular, higher temperatures could contribute to droughts and interfere with the ability of plants to pollinate. Recent studies show that rising temperatures associated with climate change may be detrimental to crop production. A study that evaluated data collected by the International Rice Research Institute between 1979 and 2003 found that increasing the mean minimum temperature by just 1° Celsius during the dry cropping season was associated with a 10 percent reduction in grain production.[43] A second study in the United States, relying on data between 1982 and 1998, came to similar conclusions—with a 1° C temperature increase corresponding to a decrease of roughly 17 percent in both corn and soybean yield.[44]

Despite the huge risks of climate change—and in particular shifts that occur more rapidly than most species and ecosystems can adapt—bioenergy crops may offer a strategy for mitigating the damage. Perennial energy crops, with their semi-permanent roots, can help soils survive both floods and droughts, and hardy energy crops can be an alternative for farmers in areas where the climate is no longer appropriate for their traditional crops.[45]

6.5 Global Scenarios for Biomass Production

Several long-term models have attempted to assess the potential of biomass to meet world energy needs, and provide interesting results. As discussed, bioenergy potential can vary greatly depending on such factors as the availability of marginal land, the relationship between increasing agricultural productivity and increasing food demand, the extent of international food trade, and the effects of climate change.

In 2004, Hoogwijk detailed four scenarios for bioenergy production based on models published in the Intergovernmental Panel on Climate Change's (IPCC's) *Special Report on Emissions Scenarios (SRES)*.[46] (See Figure 6–2.) The models describe futures with very different social, economic, technological, environmental, and policy developments, constructed along two dimensions: the degree of globalization versus regionalization, and the degree of orientation toward material versus social and ecological values. In the more globalized scenarios, population growth is lower (due to declining birthrates) and agricultural efficiencies increase faster (reflecting the fact that crops are more often grown with "modern" technologies, in their best environments, and then traded internationally). In scenarios that place greater emphasis on social and environmental values, people east less meat and larger portions of land are set aside for conservation purposes.

In the so-called B1 scenario (the environmentally and globally oriented combination), the estimated potential for bioenergy production exceeds the total primary energy demand for that particular future. In contrast, the A2 (materialistic and regionally oriented) scenario results in the highest total energy demand and the lowest biomass potential. Thus, while the share of biomass in the total energy mixture could reach 100 percent in an environmental-global scenario, it would always be limited in a material-regional world (contributing only around 22 percent of total energy).[47]

The potential for using abandoned agricultural land is the largest in the two globally oriented scenarios (A1, B1). In these cases, the potentials are comparable to the present world energy consumption of about 430 EJ per year, and the regions with the most significant potentials are the former Soviet Union, East Asia, and South America. One reason for higher use of marginal land in these scenarios is that both describe a world where population growth is low and technical development is high, thus avoiding issues of food competition or poor agricultural efficiency. In the global-environmental scenario (B1), competing land-use options such as conservation restrict biomass potential more than in the global-material scenario (A1), though large quantities of land are still potentially available.[48]

Figure 6–2. Schematic Description of the Four Scenarios Used by Hoogwijk

Material/ Economic			
A1		**A2**	
Food trade:	maximal	Food trade:	low
Consumption of meat:	high	Consumption of meat:	high
Technology development:	high	Technology development:	low
Average management factor for food crops:	2050: 0.82 2010: 0.89	Average management factor for food crops:	2050: 0.78 2100: 0.86
Fertilization of food crops:	very high	Fertilization of food crops:	high
Crop intensity growth:	high	Crop intensity growth:	low
Population:	2050: 8.7 billion 2100: 7.1 billion	Population:	2050: 11.3 billion 2100: 15.1 billion
GDP:	2050: 24.2 * 10^3 billion $\$_{95}$ Y^{-1} 2100: 86.2 * 10^3 billion $\$_{95}$ Y^{-1}	GDP:	2050: 8.6 * 10^3 billion $\$_{95}$ Y^{-1} 2100: 17.9 * 10^3 billion $\$_{95}$ Y^{-1}
Global oriented			**Regional oriented**
B1		**B2**	
Food trade:	high	Food trade:	very low
Consumption of meat:	low	Consumption of meat:	low
Technology development:	high	Technology development:	low
Average management factor for food crops:	2050: 0.82 2100: 0.89	Average management factor for food crops:	2050: 0.78 2100: 0.89
Fertilization of food crops:	low	Fertilization of food crops:	low
Crop intensity growth:	high	Crop intensity growth:	low
Population:	2050: 8.7 billion 2100: 7.1 billion	Population:	2050: 9.4 billion 2100: 10.4 billion
GDP:	2050: 18.4 * 10^3 billion $\$_{95}$ Y^{-1} 2100: 53.9 * 10^3 billion $\$_{95}$ Y^{-1}	GDP:	2050: 9.4 * 10^3 billion $\$_{95}$ Y^{-1} 2100: 27.7 * 10^3 billion $\$_{95}$ Y^{-1}
Environment/ Social			

Source: See Endnote 46 for this chapter.

Of the four scenarios, the regional-materialistic world (A2) has the lowest bioenergy potential. It is a world with rapid population growth, where agricultural trade does little to improve inefficiencies in global land use.

6.5.1 Geographic Potentials for Harvesting Biomass Energy

In a different study, Smeets et al. (2004) also modeled four scenarios for 2050 and came to several useful conclusions about the potential for bioenergy production in different geographic regions. The results are presented in Appendix A–6, and are summarized as follows:

- In terms of *overall biomass production*, Latin America, sub-Saharan Africa and Eastern Europe are particularly promising regions. Oceania and East and Northeast Asia also have potential over the longer term, as population growth in these regions slows by 2030 and as rapid technological progress in agriculture leads to substantial productivity increases.

- The *largest potential surplus cropland* is in Latin America and the Caribbean and in sub-Saharan Africa. Potential cropland in Latin America and the Caribbean could provide for 87–279 EJ of bioenergy per year), and potential cropland in sub-Saharan Africa could provide for 49–347 EJ of bioenergy per year). The high bioenergy potential in these regions stems mainly from the large areas of surplus pastureland currently in use as well as currently inefficient production systems and land use.

- The *most land-stressed regions* are the Near East and North Africa, South Asia, and parts of East Asia. These regions would need to meet their energy needs through imports from other regions. However, they have some bioenergy production potential in areas currently classified as not suitable for crop production.

- The *most robust* of all regions is the Commonwealth of Independent States (CIS) and the Baltic States. It has a considerable biomass production potential equal to one-fifth to one-third of the total agricultural land use, with a bioenergy potential of 83–269 EJ per year. Due to the collapse of communism and subsequent economic restructuring, income, consumption, production, and agricultural yields in the region have all decreased, and it will take several decades before consumption levels again reach levels common in the Soviet period. In addition, the population is projected to decrease by 2050. Consequently, the agricultural land area is relatively large compared to the projected demand for food.

- The industrialized region with the largest potential to boost yields and reduce the area of conventional agricultural land is Oceania. Between 42–84 percent of the total agricultural land in use in this region in 1998 could be abandoned and used for bioenergy production, equal to 40–114 EJ per year.

- North America, meanwhile, has the potential to produce 39–204 EJ of bioenergy per year, despite a projected increase in population. Processing forest and agricultural residues account for 19–24 EJ of this annual potential.

- Worldwide, the surplus production potential of wood from natural forests is estimated at 20–36 EJ per year. However, various limiting factors, such as the exclusion of undisturbed forests or the possibility that forest use is economically unattractive, may reduce or eliminate this potential.

Exploiting the bioenergy potential described here would require major efforts, and in particular significant improvement in agricultural efficiency in developing countries. It is uncertain to what extent and how rapidly such transitions can occur. Under less favorable conditions, the regional bioenergy potential could be quite low. Also, it should be noted that technological developments in the conversion of biomass into transportable pellets and liquids, as well as long-distance biomass supply chains, dramatically improve the competitiveness and efficiency of bioenergy.[49]

6.5.2 Cost-Supply Curves

The relative costs of producing energy crops will develop over time. They may increase due to the rising cost of labor, or decrease due to improvements in yield. Based on the four scenarios by Hoogwijk described above, global cost-supply curves have been constructed for the year 2050. They show that in 2050, a significant share (130–270 EJ per year) of the biomass production potential may theoretically fall below €1.65 ($2) per gigajoule (GJ). This price is comparable to the upper level of the price for coal. In large areas in the former Soviet Union, energy crops could potentially be produced at even lower costs. The lowest costs are in East Africa, at only €0.66 ($0.8) per GJ (achieved in the A1, materialistic-globally oriented scenario).

6.5.3 Improving the Models

While the literature examining the global potential for biomass energy has improved in recent years, it needs further refinement. In particular, a next step in these assessments is moving beyond more abstract analyses and making specific estimates of the *economic* and *implementation potential* for bioenergy. In particular, data is lacking on: the use and sources of fuelwood; feed composition and feed conversion efficiencies; production capacities of natural pastures and the impact of various management systems; the extent and severity of environmental degradation and the impact of various management systems; sustainable forest management; and the impact of wood harvests.[50]

There is also a lack of information on the relationship between socio-economic systems and land-use patterns and yields—in particular the impact of large-scale energy crop production on the cost of land and other production costs. Further, substitution correlations between various production factors (substitution elasticities) are relatively unknown and should be addressed in national and sub-national case studies. Estimates of biomass potential need to be presented carefully, emphasizing the range of variables involved and the significant risks that large-scale biomass cultivation present to both environmental quality and social stability.[51]

The next step in assessing the realizable potential of biomass energy is to begin implementing actual projects for harvesting sustainable biomass. Projects that harvest crop residues or attempt to remediate degraded land with bioenergy crops can help producers gain practical experience and results. This is a key point: the true potential for biomass energy will become clearer as it is cultivated in more situations and on a larger scale.

6.6 Competing Uses for Biomass

As the above studies have shown, the potential to harness large quantities of global biomass for energy is enormous. However, not all of this will be converted into liquid biofuels for transportation. Among the important competing uses for biomass are heat, electricity, and materials. Indeed, refining bioenergy into transportation fuels may be a less energetically efficient option than using bioenergy for heat and power. Likewise, biofuels may be less valuable than other biomaterials, such as bio-based plastics, fabrics, and chemicals, whose production is likely to take precedence.[52]

Nonetheless, biofuels are likely to draw on a significant portion of future biomass supplies. While there exist a range of other ways to produce heat and power, including wind, solar, and nuclear power, few alternatives to petroleum exist for producing liquid fuels. And although the production of biomaterials will likely continue to increase in the future, these co-products create less of a rivalry with biofuels. Not only are they likely to use only a fraction of total biomass supplies, but theoretically they can also be recycled into biofuels after the end of their productive life.[53]

6.6.1 Heat and Power

When considering the use of biomass for heat and power versus fuel, it is important to note that, unlike the burgeoning options for producing biofuels, there are already well established and widely used technologies for converting lignocellulosic biomass into heat and power. Moreover, just as new biofuel conversion technologies are becoming economical, gasification technologies such as integrated gasification/combined cycle systems are simultaneously making the conversion of biomass into electricity more competitive.[54]

Nonetheless, there is not a considerable difference in the cost of using biomass for electricity versus using it to produce the next generation of biofuels. Indeed, both routes can achieve competitive cost levels compared to fossil fuel based power and fuel production when primary biomass resources are available at about €1.65—2.48 ($2–3) per GJ. Still, fluctuations in the price of primary fuels (coal, natural gas, and oil) can strongly affect the attractiveness of using biomass for one application or the other. A high price for petroleum and a low price for coal would combine to make biofuel production more desirable.[55]

In the longer term (beyond 2020), a scarcity of cheap, conventional oil, combined with rising demand for transport fuels, will make next-generation biofuels an increasingly attractive use of biomass compared to power and heat. For strategic reasons as well, developing an alternative fuel to petroleum may be the preferred route for use of biomass resources. As an energy resource, oil has a far more constrained supply than coal, the dominant resource for power generation. (See Chapter 7 for a discussion of oil security.)

If the primary goal is to reduce the threat of climate change, however, biomass can reduce carbon emissions more by displacing coal (for electricity) than by displacing petroleum (for fuel). Co-firing biomass in coal-fired power stations has a higher avoided emission per unit of biomass than does using biomass to displace diesel or gasoline. This is true even when next-generation biofuels are concerned.[56] (See Chapter 11 for more on climate mitigation issues.)

Even so, there are far fewer alternatives for reducing the greenhouse gas emissions associated with liquid transportation fuels than for reducing those associated with electricity conversion.

Alternative energy options for power generation include wind energy, photovoltaics and other solar technologies, geothermal power, small-scale hydropower, natural gas, nuclear power, and potentially carbon capture and storage. It is thus likely that using biomass for transport fuels will gradually become more attractive from a carbon-mitigation perspective. In the shorter term, however, careful strategies and policies are needed to avoid brisk allocation of biomass resources away from efficient and effective utilization in power and heat production.

Policy supports currently favor the production of biofuels. As of early 2006, tax exemptions in Europe were supporting biofuel production more than feed-in tariffs and carbon taxes support biomass for heat and power generation. Although these policies presently favor conventional liquid biofuels, in the future they could favor next-generation biofuels converted from lignocellulosic biomass.[57]

It should be noted that all next-generation biofuel production facilities can be equipped to generate all or a portion of their own heat and power from biomass, in addition to producing biofuels. For gasification facilities, which can produce both electricity and liquid fuels, the output of power and fuel can vary over time, possibly leading to operational and economic advantages for plant owners. New large-scale conversion of biomass can therefore add to the flexibility of the energy system as a whole, bringing an important strategic benefit for the coming decades.[58]

6.6.2 Biomaterials

The use of biomass for materials ("biomaterials") can be an important competitor to applications of biomass for energy. Furniture, building frames, packaging, clothing, and paper are already significant biomaterials, and, as discussed in Chapter 5, bio-based plastics and fabrics are likely to become more important in the future. Trends indicate that the future demand for biomass as a feedstock for materials will surpass the historic demand for biomass as a source of energy. However, this demand does not necessarily rival the supply of biofuels.[59]

The use of biomass for biomaterials will increase both in well-established markets (such as paper and construction) and in large, new markets (such as biochemicals and plastics, and use of charcoal for steel making). Given that many biomaterial applications have a high economic value, this adds to the competition for biomass (in particular forest biomass) and land resources for producing woody biomass and other crops. On the other hand, increased demand for biomass for energy will increase feedstock prices for material applications. Such price effects are already observed with forestry and paper pulp products, in particular triggered by financial support of bioenergy applications in places such as Europe.[60]
However, biomaterials can be recycled, and eventually down-cycled into feedstocks for biofuels. Construction wood ends up as waste wood, paper as waste paper, and bioplastics as municipal solid waste. Such waste streams are also biomass feedstock and are often available at very low or even negative costs. Dornburg et al. (2005) have investigated the climate and economic impacts of "cascading" biomass in this way. They conclude that this strategy for using biomass could provide very large CO_2 reductions when compared to using biomass directly for energy. Although this is not true for every combination of biomaterial and biofuel, such recycling is a promising strategy.[61]

6.7 Conclusion

The potential for harnessing large quantities of biomass energy is very large. Biomass can theoretically rival fossil fuel supplies, although the longer-term potential for biomass resources varies widely and depends on factors that can be hard to predict. If the human population increases only slightly, vegetarianism remains a prevalent diet in much of the world, and agricultural yields continue to increase, then there could be a large reservoir of biomass energy to tap. If, however, the human population doubles and the demand for meat and dairy products continues its rapid rise, while climate change and limited investment in poor rural areas impede growth in food crop yields, then there may be only very limited supplies of biomass energy.

The large-scale cultivation and harvesting of photosynthetic energy brings with it a different set of challenges and concerns. While fossil fuels pose a greater threat to greenhouse gas concentrations, biomass fuels potentially pose a greater threat to wild ecosystems, soil quality, and water use. At the same time, should biofuels be cultivated carefully, they might also bring net ecological benefits. Perennial crops in particular can bring advantages: they have the potential to sequester carbon, diversify the habitat of old farmland, and maintain or restore the soil of degraded or marginal lands. At best, the value of biomass will provide an economic motive for prudent ecosystem management.

The "modernization" of agriculture is one key to achieving the high-end of biomass' potential. Policy makers will want to evaluate the best ways to mechanize agricultural systems, increase inputs, and increase the efficiency of meat production.

Freer international trade in both food and biomass could help expedite the development of bioenergy resources, as both food and energy crops are grown in their best conditions and then traded. However, domestic environmental laws and international certification standards would be necessary to ensure that biomass is not cultivated recklessly. (See Chapter 18.)

Biomass should also be encouraged as part of a strategy to aid rural communities. Should biomass be harvested for export, it may be cultivated at the expense of rural residents, who may be removed from their land by large-scale plantation efforts. At the same time, a new market for agricultural goods could bring additional income to farmers, and provide them with the capital they need to increase their crop efficiencies and yields. (See Chapter 8.)

There are considerable volumes of forest and agricultural residues and organic wastes available, but large-scale harvesting of dedicated energy crops is still minimal. The rapid development of global bioenergy will mobilize residue and waste resources quickly, as these are often cheaper and more readily available. But over the next 10–20 years, the active production of energy crops will likely become more widespread. It is important that the critical lessons about sustainable harvesting of bioenergy crops be learned during this early expansion, which, notably, will occur even before the next generation of biofuel conversion technologies permits significant production of cellulosic biofuels.

In order to refine assessments of the true potential for cultivating biomass energy, and in order to learn how best to harvest biomass sustainably, it is important to begin accumulating and evaluating practical experience. Analyses could then extrapolate from real experience with introducing biomass production systems into the agricultural sector, and onto marginal lands, while also testing the socioeconomic effects of different harvesting schemes on the economic health of rural communities in different contexts. As biofuel production technologies mature, so should agronomic techniques for harvesting cellulosic biomass mature.

As a feedstock for producing liquid transportation fuels, biomass is perhaps the best candidate for replacing petroleum fuels. The technologies available to convert lignocellulosic fibers into liquid fuels have so far produced only negligible amounts of fuel for transportation, and it will take some time to ramp up the production of such fuels. In the meantime, biomass is already used widely as a fuel for producing heat and generating electricity, and ramping up the available supply of bioenergy will likely improve the prospects for the future conversion of this biomass into liquid fuels for transportation. Policy makers might thus expedite the use of biomass for biofuels by increasing the use of biomass for all purposes.

PART III. KEY ECONOMIC AND SOCIAL ISSUES

Chapter 7. Economic and Energy Security

7.1 Introduction

Mobility is critical to the supply of goods, food, and labor. Yet the transportation infrastructure that underpins today's economy is vulnerable, due in part to its overwhelming dependence on a single fuel source. Petroleum fuels provide an estimated 96 percent of global energy for transport.[1] Oil reserves are concentrated in a relatively small number of countries, many of them beset by economic and political problems that threaten their stability. Myriad political, environmental, and economic factors are making trade between oil exporters and highly dependent importing nations increasingly tense and vulnerable to disruption.

Biofuels offer a large-scale alternative to petroleum-based fuels for transportation. They have the ability to diversify fuel supplies and thereby alleviate pressures on the oil market. Biofuels can reduce the level of oil import dependence in many nations and can strengthen their rural economies by redirecting spending that otherwise would have been sent abroad. However, biofuels alone cannot meet increasing global energy demands for transport, and must be paired with greater efficiency and other demand-reduction strategies if a more sustainable transportation economy is to be achieved.

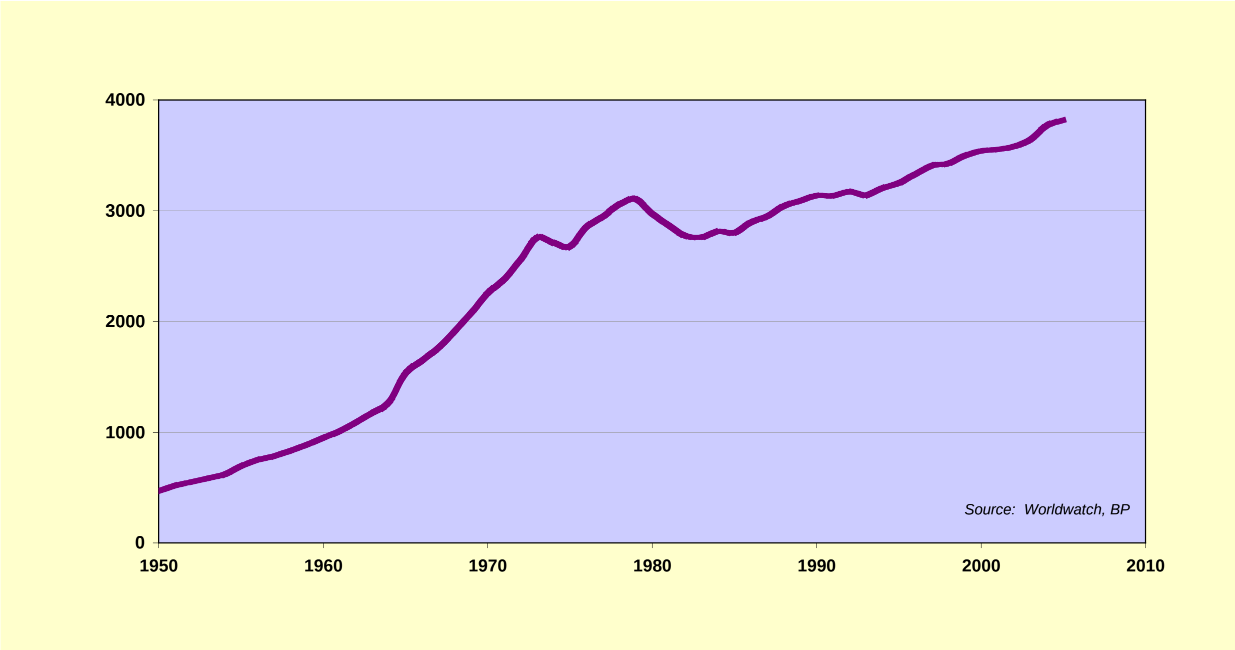
This chapter discusses the role of oil in the global economy and explores ways that expanded biofuels development could benefit economic and political relations. It describes how changing oil prices and increased petroleum demand contribute to economic and civil insecurity, and points to some of the potential advantages biofuels bring in these areas. The chapter also provides a comparison of different government supports for oil versus biofuel production and examines how biofuels may affect global prices for food and other agricultural commodities.

7.2 Rising Demand for Liquid Fuels

Over the past fifty years, world oil consumption has surged steadily upward, and in recent years, oil producers have begun to have difficulty keeping up with the pace of demand, which is now roughly 85 million barrels per day.[2] (See Figure 7–1.) This has pushed real oil prices to their highest levels in two decades, causing increasing economic hardship, particularly for poorer oil-importing countries. Unlike in the past, when oil shortages were met with increased production from Persian Gulf producers, oil producers are now operating with little excess capacity to release when supplies become tight.[3]

Rising demand for liquid fuels has led to increased investment by oil companies and is projected to add 3.6 million barrels of oil production capacity in 2006, 3.7 million in 2007, and 3.1 million barrels of capacity in 2008; however, this is far short of rising energy demand, and ExxonMobil reports that more than half of the world's hydrocarbon needs over the next 15 years have yet to be found.[4] Notwithstanding, oil price forecasts vary, and some predict the return of lower prices in the coming years, a trend that could have serious implications for investments in biofuels and other liquid fuel alternatives. Factors including climate priorities and dependencies on oil as well as security will all come to bear on the oil market of the future.

Figure 7–1. World Oil Consumption, 1950–2005

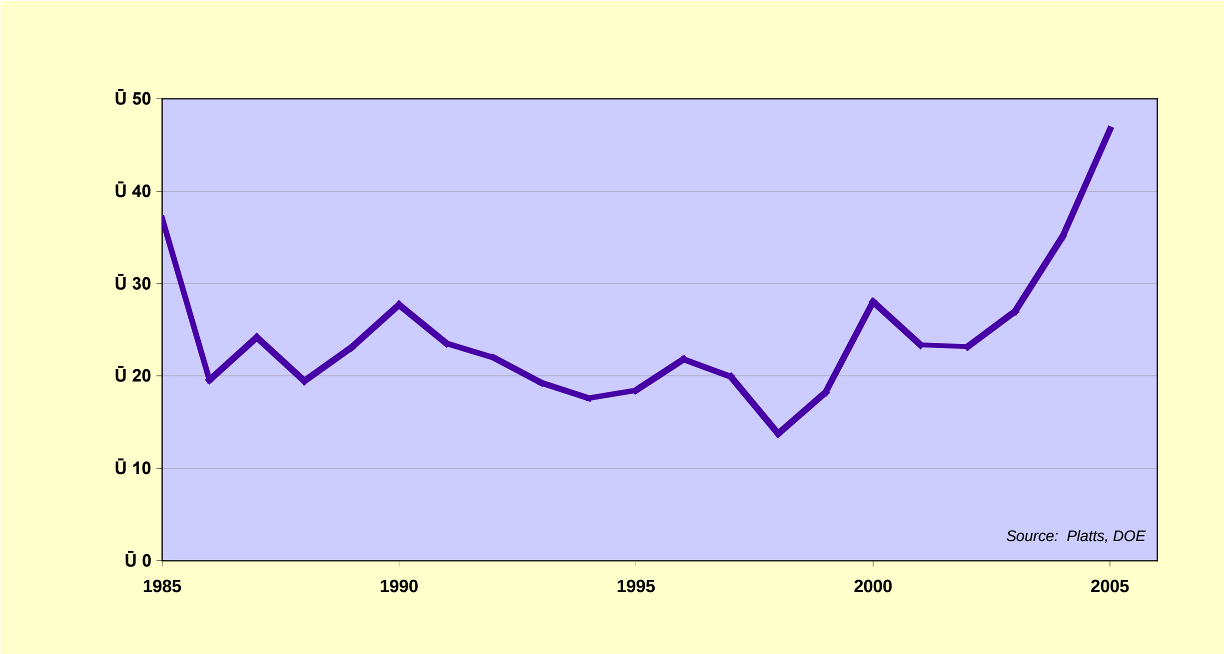


The implications of this tight oil market were evident in late 2005 and early 2006 as oil prices ranged between $60 and $70 a barrel. The price spike that followed two major hurricanes in the U.S. Gulf Coast region demonstrated the additional vulnerability of today's oil-based fuels market.[5] (See Figure 7–2.) The effects of skyrocketing oil prices were apparent in Latin America, where importing countries witnessed rising inflation and a slowdown in consumer demand.[6] And in parts of Asia and Africa, public unrest ensued as governments tried to lower oil subsidies—traditionally kept high to maintain low prices for consumers—in response to upwardly spiraling oil costs.[7]

In 2006, the increased demand for oil worldwide has kept prices high, and the situation is not expected to change anytime soon. The rapidly industrializing economies of China and India in particular are projected to increase their consumption of petroleum fuels dramatically in the coming decades, as levels of consumer spending and car ownership rise. In China alone, car ownership is projected to rise by 15 percent per year; with an estimated 28 million private cars on the road in 2005, petroleum consumption already accounted for 81.2 million tonnes, or 594 million barrels, nearly one-third of the Chinese total.[8] Along with other developing countries, China is projected to account for more than two-thirds of global energy demand by 2030.[9] Chinese demand for oil alone jumped by 36 percent between 2002 and 2005, to represent more than 8 percent of global demand, and China is now the world's second largest petroleum consumer after the United States.[10]

As conventional crude oil supplies appear less able to satisfy growing energy demand, non-conventional oils, such as tar sands, shale oil and synthetic petroleum that must be extracted under difficult geographical or climatic conditions, are increasingly being developed as substitutes.[11] However, these supplies are more costly than conventional petroleum in both economic and environmental terms, as they tend to involve more disruptive extraction techniques and are more greenhouse-gas intensive to refine. (See Chapters 11 and 13.)

Figure 7–2. Spot Crude Oil Prices (West Texas Intermediate Price), 1985–2005



7.2.1 The Power of Oil Exporting Nations

In the past, oil-producing nations have sometimes used their power over supply and distribution to achieve specific political or economic ends. For instance, both the United States (when it was a net oil exporter) and the Arab members of the Organization of Petroleum Exporting Countries (OPEC)—home to 65 percent of the world's proven oil reserves—have imposed oil embargos for political or economic reasons.[12]

International oil trade is a major contributor to the flow of capital worldwide and has considerable influence over the global economic and political system.[13] During the oil shocks of the 1970s and 1980s, industrial-country banks were flooded with "petrodollars," which in turn encouraged the widespread lending that precipitated the debt crisis in Latin America.[14] In 2005, in a period that has seen the highest sustained oil prices since the 1970s, oil-exporting countries earned record profits. Compared with the oft-touted account surpluses of the rising Chinese economy (6 percent in 2005), Middle Eastern oil exporters earned surpluses averaging 25 percent of GDP in 2005.[15]

Oil prices are a key driver of the global economy, and oil price fluctuations determine the direction of large-scale currency flows in the global market. When prices are high, oil-exporting countries earn huge profits and see their accounts expand, while the accounts of oil-importing countries swing towards deficit. Oil revenues have brought some nations, including Norway and Kuwait, great economic success; others, however, have been plagued by corruption and environmental degradation.

Roughly four-fifths of the world's oil reserves is now controlled by state-owned oil companies. Many oil-exporting countries continue to invest in private equity and other financial funds managed largely in Western economies (a factor that some experts say cushioned the blow of the 2005 oil price spikes to the American economy). At the same time, however, further development of local financial markets—as well as the desire to provide more infrastructure at home, improve oil production and refining capabilities, and provide for future economic development—is keeping more petrodollars in oil-producing nations than ever before.[16]

7.2.2 Oil Security

Heavy dependence on oil can have negative impacts on importing and exporting nations alike. Canada, China, India, Japan, and the United States join Europe in facing significant energy and environmental challenges, most notably from climate change and increasing security costs that result from oil dependency.[17] The ease of transporting oil and its utility and relatively low cost over the last century gave rise to the oil-dependent global industrialized economy. Oil dependency has at times led to military intervention to assure the steady supply of oil. In addition, climatic changes, including more severe storms, resulting from rising fossil fuel use, are increasingly apparent. (See Chapter 11 for more on climate.) Also, as indicated above, lack of spare production capacity precipitates dramatic oil price increases, leaving nations with oil-centric energy portfolios in dire financial straights.

Furthermore, as oil supplies in many parts of the world begin to dwindle in the years ahead, dependence on Middle Eastern oil is expected to grow, leaving the entire world more vulnerable to social and political developments in one of the world's least stable regions. In fact, of the world's known potential of conventional petroleum (364 billion tonnes), more than 70 percent is located in the so called 'strategic elipse,' an area spanning much of the Middle East and Central Asia which is also home to 69 percent of known natural gas reserves.[18] The European Commission estimates that European energy import dependency will rise to approximately 70 percent of the Union's energy requirements in the next 20 to 30 years, compared to 50 percent today, from regions threatened by insecurity.[19]

Any significant interruption of oil flowing through the Persian Gulf in today's market conditions would likely send oil prices over €83 ($100) per barrel. And because the price of oil is set in a single integrated market, consumers around the world would be affected by such a development, even if their own supplies came from nearby fields. Outside of challenges resulting from concentration of energy resources in OPEC and the Persian Gulf, other barriers to increased supply present themselves. For example, in Russia the re-nationalization of the oil and gas industry through Gazprom and other state companies, has given Moscow increasing power over its Western European counterparts, as evidenced by the Ukraine incident in the fall of 2005.

All told, 80 percent of the world's conventional oil reserves are under state control and off limits to private investment. Widespread state ownership and declining existing reserves leaves the world's six largest publicly traded oil firms projecting falling production over the next two years and global consumers with rising prices due to more limited supply unless affordable liquid fuel alternatives are quickly developed.[20] In sum, oil is unlikely to be a stable or secure supply of energy in the years ahead—and most nations are in urgent need of a more diverse energy supply.

Large concentrations of easily extractable resources can allow elite groups in oil-exporting nations to assert economic and political control and reduce the need to implement reforms that would allow a more diversified economy to develop. [21] This concentration of power, as well as the lack of economic opportunities for a majority share of the population, has contributed to the rise of insurgent groups and religious fundamentalism in some regions. The so-called "resource curse"—the tendency for nations endowed with oil to be plagued by corruption and conflict rather than being able to support growth and development—is exemplified by well-known tragedies associated with oil extraction in Angola, Congo, Sudan, and elsewhere.

7.2.3 Effects on Oil Importing Countries

Even without disruptions in supply due to political or natural crises, today's concentrated oil infrastructure poses challenges for many importing countries. In general, these economies are prone to endemic problems related to their lack of domestic oil resources: high imports contribute to growing trade imbalances and cause short-term shortages in foreign currency reserves which, coupled with inflation and currency convertibility issues, can slow economic growth.

Rising oil prices only worsen these problems. In developing countries in particular, the landed prices of crude oil and petroleum products are often considerably higher than prices on the international spot market. This is especially true in landlocked African nations, where transport costs can add up to 50 percent to the delivered price of fuel. High fuel costs put industries in countries with more rigid currencies at a considerable disadvantage: as energy prices rise, they face foreign exchange shortfalls and must bear the costs of paying more for imported fuel.[22]

Another problem for oil-importing countries is that domestic fuel subsidies, designed to lower the price of fuel for consumers, can stress already-weak economies and divert scarce resources from social and human development. As oil prices continue to rise, governments must pay even more to keep energy affordable. According to some estimates, at oil prices of €50–57 ($60–70) a barrel, weaker African countries are forced to spend a significant share of their foreign exchange earnings on petroleum imports.[23] In India, the International Monetary Fund estimates that every €7 ($10) increase in the price of oil will result in a 1 percent decrease in GDP and a 1.2 percent point deterioration in the balance of trade.[24] And in the world's very poorest countries—the so-called "highly indebted poor countries" (HIPCs), many of which are in Africa—sustained crude oil prices would cancel all the benefits of debt cancellation proposed at the G-8 Summit in 2005.[25]

7.3 The Biofuels Alternative

Compared with oil, biofuels can reduce many of the vulnerabilities associated with today's highly concentrated energy economy. Petroleum fuels rely on a narrow, concentrated network of extraction, refining, and distribution, with most transported by ship to a limited number of refineries, and then by ground or pipeline to market. Biofuel production, in contrast, is considerably less concentrated because of the large land area needed to cultivate the feedstock and the low energy density of this feedstock, which makes it less economical to transport long distances. As a result, biofuel processing facilities are more numerous and spread over a wider geographical area, contributing to a liquid fuel supply that is less vulnerable to disruption. Biofuels also offer an opportunity for a more dispersed and equitably distributed revenue stream.

In terms of global security, biofuels are not likely to produce the same powerful or potentially dangerous alliances that oil has generated. Revenues from Brazilian ethanol, which has thus far received the largest export profits of any biofuel, are unlikely to finance groups that are politically destabilizing. Other countries with large biofuel potential—such as Australia, China, Germany, Guatemala, India, Indonesia, Malaysia, Thailand, the United States, and Zimbabwe—

will likely use biofuels to meet domestic energy needs, substituting for costly oil imports, in the near- to medium-term.

The overall scale of biofuel production, however, can greatly affect the degree of vulnerability associated with these fuels. Small-scale production, in particular, can help circumvent supply and distribution concerns by bringing both energy and profits directly to rural consumers. Locally produced fuels can also help to avoid the environmental impacts that can occur with long-distance shipping and other transport. Larger-scale biofuel production, on the other hand, may result in greater industry concentration, be of less benefit to local communities, and will likely require more complex infrastructure, such as the use of pipelines and large processing refineries. This could lead to political, economic, social, and environmental effects more akin to those with fossil fuels. (See Chapters 11 and 13.)

Although they may not face the same logistical and political vulnerabilities as oil, biofuels still remain susceptible to natural and human-caused disasters, including crop failures, irregular weather patterns, and droughts, which could increase with climate change. This vulnerability is of particular concern with biofuels produced from first-generation agricultural feedstock or next-generation feedstock derived from residues and wastes, such as municipal waste streams, are less affected by weather-related disruption.

7.3.1 The Economics of Biofuels

Biofuels also offer potential economic advantages over fossil fuels, though direct cost comparisons can be difficult. This is because varying biofuel feedstock and processing options have different costs and benefits, and because the negative externalities associated with fossil fuels—in terms of military expenditures, and health and environmental costs—tend to be poorly quantified. Although many studies have endeavored to assign prices to such factors as climate benefits, air quality improvements, human health, sustainability, and increased security, accurate quantification of these variables still proves challenging.

Biofuels can look uncompetitive if measured on a direct-cost basis. For example, the market price for biomass pellets in the Netherlands was about €7–7.5 per gigajoule (GJ) in 2004 and is expected to stabilize around €5.6–6.4 per GJ in the short term, while the cost of coal generally remains around €1.2 per GJ. Brazilian ethanol costs, however, lie between €6 per GJ ($7.2/GJ), suggesting that with continued gains in technology and efficiency, biofuels may eventually be able to compete outright with fossil fuels.[26] Biofuels also have the potential to generate many positive externalities, such as reduced greenhouse gas emissions, decreased air pollution, and job creation, making them a more socially and environmentally desirable liquid fuel.

Some developing countries in particular may be able to develop significant biofuel industries, based on the comparatively low land and labor costs and favorable growing conditions in these regions. Because feedstock costs generally represent about 80 percent of the total production cost of current-generation biofuels, overall production costs in tropical countries would be low relative to more temperate countries—as is the case with sugar production.[27] (See Table 7–1.) Increased trade in biofuels would generate more income for producing countries, reduce vulnerabilities (in part by increasing the number of producers), and result in a more diversified global supply of liquid fuels for transport.[28] (See Chapters 2 and 9.)

Table 7–1. Cost Ranges for Various Sugars and Sweeteners, Selected Regions, 1997/98–2001/02

Category	Cost of Production, Ex-Mill, Factory Basis (Eurocents per Kilogram)
Raw cane sugar	
Low-cost producers[a]	9.6–20.0
Major exporters[b]	11.2–31.6
Weighted world average	20.4–22.9
Cane sugar, with white equivalent	
Low-cost producers[a]	15.8–27.2
Major exporters[b]	17.6–39.7
Weighted world average	27.6–30.2
Beet sugar, refined value	
Low-cost producers[c]	29.6–53.1
Major exporters[d]	40.4–57.8
Weighted world average	54.2– 56.9

Notes: (a) Australia, Brazil (center-south), Guatemala, Zambia, and Zimbabwe; (b) Australia, Brazil, Colombia, Cuba, Guatemala, Zambia, and Thailand; (c) Belgium, Canada, Chile, France, Turkey, United Kingdom, and United States; (d) Belgium, France, Germany, and Turkey.
Source: See Endnote 27 for this chapter.

When comparing the environmental costs of biofuels versus fossil fuels, a biofuel market may actually provide long-term economic benefits, provided it develops in a sustainable manner. Carbon dioxide (CO_2) is one negative externality of fossil fuel use that biofuels can reduce, with benefits increasing even more dramatically with next-generation feedstock and fuel technologies. (See Chapter 11.) Through emerging carbon markets such as the EU-Emissions Trading System and the Chicago Climate Exchange, biofuels will benefit and fossil fuels will lose out as a result of their differing carbon intensities.[29] (See Chapter 12.) Although transport is not currently covered by emissions trading schemes, biofuels could be a more valuable asset in future systems that will likely include the transport sector. The Kyoto Protocol's Clean Development Mechanism may provide widespread opportunities for rural development while contributing to the reduction in global greenhouse gases, if existing hurdles to implementation can be overcome. According to a recent World Bank study, at carbon prices of €2.5–16.5 ($3–20) per ton of CO_2-equivalent, biofuels could earn €0.005–0.06 ($0.01–0.07) per liter on the carbon market.[30] (See Chapter 18.)

7.3.2 Savings From Avoided Oil Imports and Positive Externalities

Biofuels can be an especially important energy alternative in oil-importing developing countries where landed petroleum costs are high due to poor distribution infrastructure.[31] Investing in a domestic biofuels industry could not only provide increased employment opportunities in rural areas, but it would allow developing nations to internalize a share of the economic value of the locally produced fuels.[32] However, this process is neither immediate nor guaranteed, and must be supported by appropriate policy measures.

The economic savings from avoided oil imports can be considerable, but must be taken in the context of government spending required to support biofuel development. In Brazil, years of domestic support for the ethanol program allowed the country to reduce oil imports and to produce ethanol at a lower domestic cost than gasoline.[33] Between 1975 and 1987, ethanol saved Brazil €8.6 billion ($10.4 billion) in foreign exchange and cost the government €7.44 ($9 billion) in subsidies.[34] More recent studies show that from 1976–2004, Brazil's ethanol production substituted for oil imports worth €50.2 billion ($60.7 billion), or €100.3 billion ($121.3 billion) including interest on the foreign debt previously incurred financing oil imports.[35] Many countries are eager to follow Brazil's example, saving foreign exchange and retaining more money in the domestic economy.

In India, it is estimated that gradually substituting 15 percent of the current transport-sector fuel with biofuels would save some €2.1 billion ($2.5 billion) worth of foreign exchange by 2012–13.[36] And in sugar-producing countries in Central America, experts estimate that on average, domestic biofuels industries could generate more than €62 million ($75 million) annually in savings from avoided oil imports.[37] This is especially significant for countries where the rural poor are hit hard by rising energy prices: in 2005, inflation rates reached 8 percent in Guatemala and 14 percent in Costa Rica in response to 30-percent rises in fuel prices—increasing the number of people living on less than $1 a day.[38]

Some countries are already investing in biofuels development to offset oil imports. In Jamaica, where oil imports eclipsed $1 billion in 2005 and officials have declared the energy consumption-to-production ratio "economically challenging," the government recently formed a partnership with the Brazilian company Coimex to boost the ethanol content of gasoline from 5 percent to 10 percent to reduce oil imports.[39] Nigeria, meanwhile, expects to save €202.6 million ($245 million) in avoided refined petroleum product imports per year through recent biofuel investments and ethanol blending mandates.[40]

7.4 Subsidies

A variety of economic and policy instruments, including subsidies, blending mandates, and tax incentives, have been critical in spurring the development of biofuels worldwide. However, this support must be considered in the context of the support enjoyed by the global oil industry, which—despite being a mature industry—continues to receive massive subsidies to secure supply, including depletion tax credits and indirect subsidies from healthcare systems and international military presence.

While reliable quantification of global oil subsidies is nearly impossible, it is fair to say that direct petroleum subsidies are considerably larger than direct biofuels subsidies *in absolute terms*; however, the much larger size of the oil and gas industry must be considered. The U.S. General Accounting Office estimated that in the 32 years prior to 2001, the oil industry received more than €107.5 ($130 billion) in tax incentives, compared with roughly $11 billion given to the ethanol industry in the 21 years prior to 2001.[41] (See Table 7–2.) Although this does not include military and health costs of fossil fuels, U.S. subsidies to the petroleum industry, equal to roughly €0.002/liter ($0.003/liter), are far lower than the per-liter subsidy to biofuels in the United States.[42]

In terms of indirect (or implicit) expenditures for fossil fuels, in 2003 the U.S. National Defense Council Foundation estimated that some €40.6 billion ($49.1 billion) in annual defense outlays is required to defend the flow of Persian Gulf oil to importing countries—the equivalent of adding €0.26 ($0.30) to the price of a liter of gasoline.[43] Health expenditures related to fossil fuels add up as well. The U.S. Congressional Research Service estimated that the additional cost due to ozone-related respiratory health problems was €3.31 billion ($4 billion), or €0.01 per liter ($0.05 per gallon) of gasoline, while the additional cost due to morbidity and premature mortality caused by particulates and acidic aerosols was tens of billions of dollars, or €0.13 per liter ($0.59 per gallon) of diesel.[44] Estimates of environmental damage from automotive diesel, based on 1993 data, averaged €0.26 ($0.31) per liter of gasoline.[45]

Table 7–2. Tax Incentives for Petroleum vs. Ethanol in the United States, 1968–2000

Tax Incentive	Time Period	Government Revenue Losses[a] (million U.S. dollars, adjusted for 2000)
Petroleum Industry		
Excess of percentage over cost depletion[b]	1968–2000	81,679–82,085[c]
Expensing of exploration and development costs[b]	1968–2000	42,855–54,580
Alternative (non-conventional) fuel production credit	1980–2000	8,411–10,542
Oil and gas exception from passive loss limitation	1988–2000	1,065
Credit for enhanced oil recovery costs	1994–2000	482–1,002
Expensing of tertiary injectants	1980–2000	330
All Incentives	1968-2000	134,822–149,602[d]
Ethanol Industry		
Partial exemption from the excise tax for alcohol fuels	1979–2000	7,523–11,183
Income tax credits for alcohol fuels	1980–2000	198–478
All Incentives	1979-2000	7,721–11,661[d]

Notes: (a) estimates include both corporate and individual income tax revenue losses except for the partial exemption from the excise tax for alcohol fuels, which represents revenue losses from the federal excise tax on gasoline; (b) ranges are based on varying estimates given by the U.S. Department of Treasury and the Joint Committee on Taxation; (c) in some years, revenue losses associated with other fuels and nonfuel minerals were included with revenue losses from oil and gas; (d) estimates of total revenue losses are very rough; the sum of two or more incentives could result in a total change in tax liability that might have a lesser or a greater effect on revenue than the amounts shown for each item separately.
Source: See Endnote 41 for this chapter.

Financial support for biofuels is considerably lower. In 2005, the U.S. government provided direct subsidies of more than €82.7 million ($100 million) to support domestic ethanol, one of the world's largest biofuel industries. Ethanol receives about twice as much funding in the United States as biodiesel; however, per liter, biodiesel is more subsidized because it represents a much smaller share of the U.S. market.[46] Federal tax credits for the fuels were worth an additional €1.65 ($2 billion).[47] Additionally, many states provide assistance for the construction of new plants, as well as exempting biofuels from state excise taxes normally applied to transport fuels. U.S. ethanol benefits from one additional support as well: a tariff on competing imports (mainly from Brazil) of €0.12 per liter ($0.54 per gallon).

In Brazil, ethanol production was heavily subsidized from the 1930s leading up to and during the Proálcool program, launched in the 1970s. Price guarantees and subsidies, public loans, and state-guaranteed private bank loans were all used to support the ethanol industry during its development, and at one point the interest on unpaid debt from this industry alone was equivalent to €0.41 ($0.49) per liter.[48] Today, ethanol production from sugar cane in the center-south does not receive any direct government subsidies; however, Brazil employs a series of policies that secure ethanol's place in the country's energy matrix, including:

- A mandate requiring that all gasoline be blended with a minimum of 20–25 percent ethanol (flexible with respect to changing sugar and ethanol prices on the world market);

- An import tariff on gasoline that is one of the highest in the world;

- A ban on diesel-powered personal vehicles to boost the demand for ethanol-powered vehicles;

- A requirement that all government entities purchase 100-percent hydrated alcohol-fueled vehicles; and

- Low interest loans for financing producer-owned stocks.[49]

Production costs in Brazil make ethanol competitive at average crude oil prices in 2005. While many studies assessing the long-term feasibility of biofuel production are reluctant to assume that oil prices will stay high enough to keep these fuels attractive, most signs point to high oil prices in the future—including the rising cost of extracting petroleum from deeper and more remote deposits, government policies to internalize externalities, and accelerating demand. Even the fairly conservative U.S. Energy Information Administration has projected that oil prices will remain near $50 per barrel for the next few decades.[50] Biofuels will not be immune to high oil prices, and until they represent a significant share of the global market, they will continue to be price takers and shadow increases in gasoline prices.

Technological improvements can bring significant cost reductions for competitive biofuels producers as well. In the early years of Brazil's ethanol program, prices were tightly controlled by the government; but today, as a result of increasing economies of scale, technological efficiency, and biotechnology, direct subsidies are no longer required, and prices shadow the oil market and the global sugar market. Many experts feel that with increased research and development, improvements in crop yields due to genetic engineering and enzyme development for biofuels processing can further reduce the costs of ethanol production.[51] (See Chapters 4, 5, and 6.)

7.5 Biofuels and the Agricultural Market

Biofuels could also have significant impacts on agricultural markets. Global prices for agricultural commodities, including crops such as corn, wheat, and cotton, often fall below the costs of production because government subsidies and policies in industrialized countries favor urban consumers over farmers, resulting in excess supply.[52] Low agricultural prices have the greatest impact on small-scale grain and oilseed producers in developing countries, who are often unable to grow alternative crops or find other work.[53] A move toward agricultural-based energy production via biofuels could absorb excess supply, transition land away from traditional tradable corps, and help maintain higher commodity prices.

Higher prices have already been recorded for the most commonly used biofuel feedstock—corn, sugarcane, rapeseed, and palm oil—in the wake of high oil prices in early 2006.[54] According to 2006 OECD estimates, additional demand for agricultural commodities due to increased biofuel use will have the strongest impact on sugar markets with up to 60 percent increases in price by 2014. In a conservative scenario that assumes current levels of biofuels use will continue, vegetable oil prices are projected to increase by up to 20 percent and cereals will increase by four percent.[55] In a scenario that assumes sustained oil prices around €50 ($60) per barrel, the impact of additional biofuel production would increase sugar price an additional 4.2 percent and vegetable oils and additional 4.3 percent.[56] These higher prices have the potential to bring increasing profits to rural areas worldwide, increase employment, and supply a less-harmful biomass source for developing country energy needs. (See Chapter 8.)

While long-term commodity price increases could boost farmer incomes worldwide, in the short-term risk such price increases may hurt consumers in countries that are net food importers. This is especially true in the world's poorest countries where, faced with higher food prices, people tend to consume fewer high-valued goods such as meat and dairy. Although food demand is relatively inelastic, studies show that for every 1 percent increase in the price of food, consumers in developing countries decrease their consumption by three-quarters of a percent, compared to only one-third of a percent in industrialized countries.[57] Also, at times when agricultural feedstock is more valuable for food production than for energy production, this may result in shortages in biofuels, as happened in the 1990s when Brazil was forced to import ethanol from the United States.[58]

Adding biofuel production capacity as a way to take advantage of the changing availability of different feedstock sources is a good short-term response to fluctuations in commodity output and prices. However, as the markets for food, fuel, and energy become increasingly intertwined, there may be risks as well. Agricultural surpluses could turn into regional shortages, pushing prices for biofuel feedstock and related commodities, including food crops, even higher. A recent study by the Center for International Economics suggests that ethanol substitution could harm some sectors of the rural economy. Using research from Australia, it concludes that mandating a 10–15 percent ethanol blend in gasoline would increase grain prices by up to 25 percent, adversely affecting the domestic livestock industry and weakening its export position.[59] Potential savings from averted petroleum and diesel imports, valued at around €1.08 billion ($1.3 billion), would be offset by losses in livestock exports valued at around €1.74 billion ($2.1 billion), as well as by the additional cost of importing grain to make up for diverted feedstock, estimated at €314.2 million ($380 million).[60]

Continued research and development into the most integrative technologies can provide increasingly stable demand for agricultural commodities and their co-products. (See Chapter 6.) In this regard, the development of next-generation biofuels is more desirable because these make use of lower-value agricultural products, such as surplus and waste feedstock, which do not compete directly with food commodities.

In the short run, bio-refining capacity can provide a useful way to eliminate surplus when a bumper crop is harvested, or when global demand for a commodity falls. In fact, the availability of surplus sugar cane feedstock spurred India's ambitious blending mandates in 2000 (which were subsequently placed on hold as a result of drought).[61] And China's excess of grain encouraged renewed investment in ethanol in 2001, though these surpluses have now largely been exhausted. A report for the U.S. Department of Agriculture by the Energy and Environmental Study Institute found that an abundance of “centralized biomass” created the most favorable conditions for the development of biofuels and bio-based products.[62] However, regular surpluses may be indicative of a larger market failure and may not be sustainable.

Currently, regular surpluses of molasses exist in many African and Latin American countries and could be used to produce ethanol at very low prices. A large quantity of surplus molasses in close proximity to ethanol production facilities allows for economies of scale necessary to make ethanol price competitive with gasoline.[63] If trade in agricultural goods liberalizes in response to agreements under the World Trade Organization, surplus crops may not be as abundant in industrialized countries because domestic support measures must be drastically reduced. (See Chapter 9.) This could provide an increased opportunity for more-efficient producers of energy crops in developing countries to earn income, especially in Latin America and the Caribbean where agricultural products still contribute 20–30 percent of GDP.[64]

7.6 The Economic Promise of Next-Generation Biofuels

Feedstock costs for emerging biofuel technologies—such as cellulosic ethanol or the expansion of biomass-to-fuel production—are projected to be much lower than those assumed for current or conventional biofuels (where feedstock costs account for a large share of the overall production cost). (See Chapter 3.) This is because next-generation feedstock, including municipal solid waste, crop residues, animal waste, wood wastes and residues, and other waste materials, can be converted to liquid fuels at little or no cost for the feedstock—and could even result in negative costs if landfill tipping costs are considered.[65] Similarly, waste-to-fuel projects can prevent the destructive environmental effects that agriculture and municipal wastes have on streams and aquifers, and could lead to savings from avoided human health and environmental cleanup.[66] (See Chapters 12 and 13.) As wastes become more important for biofuel production, their costs may increase. Further analysis is necessary to determine how the use of crop-residues and other waste products will affect farmers’ incomes and harvesting and production techniques.

At the same time, these next-generation biofuels have the capability of being produced without the need for long-distance transport, because of the diversity of potential feedstock and the possibility of building bio-refineries near centers of demand. A recent study in the United States estimates that if all available crop residues in the country were converted to fuel ethanol, approximately 76 billion liters (20 billion gallons) of ethanol could be produced every year, corresponding to 10 times the output of the existing corn ethanol industry or the equivalent of 14 billion gallons of gasoline—more than 10 percent of current consumption.[67] (See Chapter 6 for more on future feedstock potentials.)

Perennial energy crops, such as switchgrass, miscanthus, and short-rotation forestry, represent a far more positive economic picture for farmers and fuel producers than current feedstock crops like rapeseed, corn, and soybeans. A recent University of Illinois study calculated that if the U.S. state of Illinois expanded cultivation of miscanthus as a dedicated energy crop, as the European Union has done on a small scale, it is expected to be competitive with corn and soybeans, without subsidies, within 10 years.[68] Another study by the Ceres network predicts that dedicated energy crops can earn farmers more than corn and wheat due to low fixed costs and high market prices.[69] Studies projecting the potential for this feedstock in Germany have not yielded such favorable cost projections, and national conditions with regard to agricultural production must be considered in determining future feedstock uses.

7.7 Increasing Efficiency and Demand-Reduction Strategies

When considering the economics of biofuels, it is important to note that countries and industries vary greatly in the energy intensities of their production (the output produced by each unit of energy input), leading to differing sensitivities to changing energy prices. Developing countries that are oil importers, for example, require twice the amount of oil to produce the same amount of output as countries in the industrialized world, due to less-efficient industrial production processes that use older technologies.[70] The greater the energy intensity of an economy, the more detrimental the effects of oil price hikes will be. As a result, high oil prices are significantly more crippling for oil-importing countries than for producers. India, for example, spent 16 percent more on oil imports in 2003 than it did in 2001—equivalent to 3 percent of GDP.[71]

Biofuels could provide an important leapfrogging opportunity for many developing nations, enabling them to bypass many of the economic, environmental, and social costs of petroleum fuels that industrial countries face. However*, biofuels development will not contribute to sustainable economic development in the absence of increasing energy efficiency*. Those countries with high energy intensities in their agricultural sectors will therefore need to take steps to improve the overall efficiency of production.

Agriculture has become one of the world's most energy-intensive industries, with the U.S. agricultural sector alone consuming 10 quadrillion Btu (10.55 exajoules) of energy per year, equivalent to France's entire annual energy consumption.[72] Globally, 28 percent of the agricultural energy used goes to manufacturing fertilizer, and 7 percent is for irrigation, while 34 percent is consumed as diesel and gasoline by farm vehicles used to plant, till, and harvest crops.[73] The balance is absorbed by the agricultural distribution chain, which requires energy-intensive packaging, refrigeration, and transportation. This high level of energy intensity is unsustainable and has caused producers in poorer oil importing nations to limit agricultural production when fuel prices are high.[74]

In the future, if crude import prices remain around 2006 levels of €50 ($60) per barrel, agricultural outputs are expected to fall 1.5 percent for wheat and 2.8 percent for oilseeds all else equal. However, OECD models indicate that this price of oil could stimulate increased biofuel production of up to 8 percent for ethanol in the United States and Brazil and up to 16 percent for biodiesel, dominated by the EU.[75]

A biofuels industry that is developed to minimize energy inputs and improve efficiency will result in significantly higher economic benefits, and can help to alleviate the pressure on oil supplies and increase countries' competitiveness. First-generation feedstock that require fewer fossil energy inputs for fertilizing, irrigating. and harvesting (such as Brazilian sugar cane and jatropha) will be more profitable and sustainable than more energy-intensive feedstock like corn and wheat. Next-generation feedstock, such as municipal solid waste and short-rotation forestry crops, will need to optimize energy intensity (among other factors) as well, to make these fuels as sustainable and cost-competitive as possible. Gains in agricultural efficiency from no-till technology, and more-efficient energy uses for industrial production, can also bring benefits.[76]

Efficiency choices made in the transportation sector will be decisive in determining the future prices of liquid fuels. Without improvements in vehicle fuel-economy and the development of alternative vehicle technologies and public transport, biofuels and petroleum fuels alone will be unable to meet the projected growth in fuel demand, particularly as car ownership increases in developing countries. Fortunately, high fuel prices are beginning to drive consumers towards more efficient vehicles, and many governments are offering incentives to those who purchase alternative fuel vehicles.[77]

Failure to respond to efficiency needs will result in continued environmental degradation from fossil fuel emissions and, ultimately, in loss of industry competitiveness. A case in point is the U.S. automobile industry, which despite outcry from environmental groups about the negative health and climate impacts of increased fossil fuel use, continued to increase production of sport utility vehicles (SUVs) because of the high profit margin.[78] In the wake of skyrocketing fuel prices, however, sales for SUVs fell 31 percent in January 2005 and 21 percent in February 2005, from their 2004 levels.[79] The U.S. auto industry is largely perceived to be in crisis: General Motors plans to close multiple facilities and eliminate 30,000 jobs, Ford will close 14 plants and cut up to 30,000 jobs, and Delphi (a world leader in transportation components and systems technology) is currently in bankruptcy, threatening to close plants, eliminate thousands of jobs, and slash wages and benefits for remaining employees.[80]

Manufacturers outside the United States, faced with increasingly stringent emissions standards, are incorporating biofuels and greater fuel economy into their economic strategies and vehicle design. (See Chapter 15.) Toyota's hybrid technology has already made the company far more competitive than its American counterparts, which have solicited technology-transfer agreements to utilize the Japanese automaker's engine designs.[81] Other automakers are investing in next-generation biofuels development. The leading biomass gasification company, Choren, is a joint project of DaimlerChrysler, Volkswagen, and oil giant Royal Dutch Shell.[82] Other oil companies are also beginning to invest in biofuels: the leading cellulosic ethanol developer, Iogen, is a joint venture of Royal Dutch Shell and PetroCanada.[83]

As oil prices continue to rise, the higher the energy intensity of a product, the more expensive it will become—a reality that will make energy-efficient production and processes that rely on petroleum alternatives ever more attractive. As such, biofuels may be uniquely positioned to relieve stress on the crop sector and facilitate waste reduction by providing a readily available fuel that is less vulnerable to price shocks; reduce municipal solid wastes and agricultural residues with the development of new technologies; and promote job creation. Industries developing biofuels and other alternative energy and efficiency technologies will be increasingly competitive and able to profit from global demand for these products. (See Chapter 9.)

7.8 Conclusion

Among the main economic and security advantages of biofuels are their potential to reduce costly oil imports, decrease vulnerability to price shocks and disruptions in energy supply, and increase domestic access to energy. These advantages can benefit both industrialized and developing countries. In general, industrialized countries have the option of either producing biofuels domestically or importing them on a large scale, as a substitute for greenhouse-gas intensive and increasingly expensive petroleum fuels. These countries can also advance research and development that supports the development of next-generation biofuels and their co-products (as can several biofuels leaders in the developing world, including Brazil, China, and India).

Developing countries with large agricultural potentials have the opportunity to substitute for expensive oil imports and, where profitable, develop biofuel exports, as Brazil has begun to do. Export industries could offer substantial rural economic benefits, particularly if the processing facilities are owned and operated by farmers in these countries. However, if developing countries are limited to exporting only the raw agricultural feedstock for biofuel production, the economic benefits will be reduced. Developing countries that do not have large agricultural potentials might benefit instead from small-scale biofuel production, particularly where limited infrastructure makes petroleum fuels difficult and costly to transport. Development of biofuels for local markets will more effectively displace oil imports and create greater rural employment in poorer developing countries. (See Chapter 8.)

Recognizing the potential economic advantages of biofuels, some national governments and international actors are already pressing for large-scale biofuel development through blending mandates and renewable energy targets—in effect guaranteeing a substantial amount of future demand. But biofuel promotion policies will need to consider carefully what type of development is ideal, keeping in mind that once subsidies and incentives are granted, they are often politically difficult to remove. And any country considering increased biofuels development will need to assess the feasibility of adopting different biofuels feedstock and processing infrastructures based on its unique natural resource and economic context.

The extent to which biofuels development addresses issues of oil dependence largely depends on the price and quantity of biofuels that can be produced. Historically, biofuels have been more expensive than petroleum fuels, and still today nearly all biofuel industries rely on extensive governmental support (mainly subsidies) to be viable. Moreover, most biofuel crops can displace only a limited amount of oil before rising demand for feedstock puts upward pressure on the prices of agricultural commodities, and therefore food. These pressures on commodity prices are likely to be beneficial for farmers in the medium and long term despite short-term risks. (See Chapter 8.)

Thus, while conventional biofuels have great potential to displace oil—particularly in tropical countries—it is only the development of the next generation of feedstock and conversion technologies that will really determine the full potential of biofuels to diversify the world's liquid fuel supply in an economically viable manner. As these technologies emerge, preference should be given to approaches that use waste streams and perennial energy crops as feedstock. Use of these feedstock and technologies can positively affect food commodity prices by taking agricultural land out of production and reducing surplus production, and potentially increasing the price of low-value agricultural products. This would minimize competition with food and animal feed and contribute to healthier social, environmental, and economic outlooks. (See Chapters 8 and 9.)

No matter how successful an emerging biofuels industry is, however, without significant innovation to make the transportation sector more efficient overall, especially in the United States and growing markets like China and India, demand for liquid transport fuels is likely to produce market conditions that encourage the production of petroleum and biofuels at a level that is not environmentally sustainable. Strong environmental and social protections, rule of law, and governance will be key to the overall success of biofuels.

Chapter 8. Implications for Agriculture and Rural Development

8.1. Introduction

Beginning with their earliest advocates, biofuel programs have aimed to support agricultural economies. Henry Ford and even Rudolph Diesel promoted the use of liquid fuels from plant sources as a way to expand the market for farm products. Today, most biofuel production efforts are still set up primarily to help domestic agricultural producers and rural economies.

The need to bolster rural areas is critical. Most of the world's hungry people live in farming regions, and smallholder livelihoods are increasingly threatened by the expansion of mechanized industrial agriculture. In the developing world, this mechanization is contributing to a massive migration from rural communities to urban areas, where economic prospects are often no better. Even in the industrialized world, where most people already live in cities, the farming population has declined steadily as larger and more capital-intensive farming operations eliminate agricultural jobs.[1]

This chapter discusses the potential for biofuel development to aid rural areas. It explores how these fuels can increase market demand for agricultural products, as well their potential to boost agricultural employment and substitute for agricultural subsidies. In addition, the chapter briefly examines the merits of the "food-versus-fuel" debate and highlights some of the risks to rural communities of more concentrated and larger-scale biofuel production.

8.2. Expanding Markets for Agricultural Products

Expanded biofuel production can offer particular benefits to people living and working in the world's agriculture regions. Biomass depends on agriculture and forestry, and it is available in nearly every region of the world. Moreover, as mentioned previously, the economies of scale that dominate the petroleum industry do not apply as readily to the harvesting and processing of biofuels, making the liquid biofuel industry less concentrated and more labor intensive than the fossil fuel industry.

Creating a market for biofuels as a way to increase the value of the world's farm products is an obvious plus for the agricultural economy as a whole. However, higher crop prices do not automatically translate into better conditions for farmers or rural communities; for instance, they can raise the price of inputs for the meat and agricultural processing industries. They can also fail to trickle down to the poorest participants in the agricultural economy.

8.2.1 Larger Markets and Higher Prices

Historically, biofuel programs have served the purpose of providing farmers with both a larger market and a price support. In the early 1900s, the French government promoted ethanol production as a way to handle a decline in sugar beet exports. Germany offered a subsidy to keep ethanol prices on par with gasoline, largely to boost demand for domestic grain. And in the United States, early fuel ethanol policies were established as a way to handle the surplus of grains, potatoes, and sugar beets that resulted from agricultural exploitation of virgin western lands.[2]

Today, biofuel production still helps to maintain or increase the price of certain agricultural feedstock. In the United States, rising ethanol production has absorbed a steadily larger share of the country's corn crop, from 12 percent in 2004, to a predicted 18 percent for 2005–06, to a projected 20 percent-plus by 2012.[3*] This rising demand for corn feedstock for ethanol is expected to keep crop prices high. According to analysts at the University of Missouri, by 2012 increasing demand **c**ould raise the price of corn by an average of €0.11 ($.013 cents) per bushel and increase net farm income by €246 million ($298 million) per year.[4†] Additional demand for corn would also raise the prices of sorghum and wheat, by €0.07 and €0.05 ($0.09 and $0.06), respectively.[5]

In the European Union (EU), policymakers have developed the market for biodiesel in large part to support growers of oilseed crops. Limited by the Blair House Agreement, which restricts the amount of acreage that can be planted with oilseeds for food, farmers have instead planted rapeseed and sunflower seed for use in biodiesel fuel. The market has grown so rapidly that more than 20 percent of EU rapeseed is now sold for fuel.[6] This market expansion has also caused rapeseed oil prices to reach new highs at the Rotterdam market.[7]

The advent of the Proálcool program in Brazil, designed to spur the domestic market for ethanol and keep sugar prices high, led to an expansion of the area planted for sugar cane that still continues today. Since about 50 percent of the country's sugar is converted into ethanol, the biofuel program has effectively permitted a doubling of planted acreage—perhaps more, since most of the country's mills are integrated facilities that can hedge between sugar and ethanol, and are less risky than sugar-only mills.[8] High gasoline prices and increased demand for ethanol fuel in Brazil over the last few years has been a key factor in the rise in the global price of sugar to today's 10-year high.[9]

Other countries are also pursuing biofuel programs with the aim of expanding the market for common crops. Australia's northern sugar growers have experienced a 20 percent drop in the price of their sugar, despite high international prices between 1999 and 2004, and have turned to a domestic fuel ethanol program to provide a more stable market.[10] And French wine growers are hoping that fuel ethanol production will help them cope with recent overproduction.[11] Likewise, corn producers in South Africa are struggling with a glut of overproduction and are using these surpluses as collateral to finance the construction of eight ethanol facilities, creating a long-term additional market for the crop.[12]

Elsewhere in the developing world, Malaysia and especially Indonesia are rapidly expanding their palm oil acreage, hoping that rising European biodiesel demand will help boost their exports by 30 percent or more in the coming years.[13] Thailand's ethanol blending mandate has already increased the price of cassava, and the government is reversing its sugar cane restriction policy to encourage more domestic production.[14] In the Philippines, legislators have been planning to introduce a biodiesel blending mandate to support the country's nearly five million coconut farmers, and an ethanol mandate to help reverse shrinking acreage in the sugar cane industry.[15] (See Chapter 17.)

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[*] This 20 percent projection is based on the U.S. Renewable Fuel Standard target of 7.5 billion gallons of biofuel for 2012.

[†] In contrast, increased ethanol production results in more production and lower prices of corn by-products. Soybean meal prices are reduced by 10 percent.

While higher crop prices are clearly beneficial to some crop producers, other industries can suffer—in particular those that purchase agricultural feedstock. In Europe, the increased demand for biodiesel has caused shortages of rapeseed oil, sending makers of margarine, mayonnaise, and salad dressing scrambling for alternative supplies.[16] The Australian beef industry, wary of rising prices for feed grain, has warned than a grain-ethanol program may lead to greater losses in meat exports than gains from avoided oil imports.[17] And in the United States, one study concluded that hog and poultry producers, along with operators of grain processing and exporting facilities, would lose out as more corn is diverted to ethanol.[18]

8.2.2 New Feedstock and New Markets

Some of these problems could be avoided as a wider diversity of feedstock is used and as new technologies for biofuels are developed. (See Chapters 4 and 5.) This would further diversify the variety of farm products produced, open up new markets for underutilized forms of biomass, and make more land area available for agricultural use. It could also alleviate some of the competition for existing agricultural commodities.

Jatropha, an oil-yielding tree that can grow on degraded soils in arid conditions, is one promising feedstock that would not have to compete for valuable agricultural land. A UK company, D1 Oils Plc., has made arrangements to cultivate it along train tracks in India, on mining-degraded soils in the Philippines, and on a wastewater dumping ground in Egypt.[19]

Additionally, a wide range of crop residues, traditionally left to decay in the fields, could be converted to fuel using new cellulosic technologies, offering farmers a second harvest from their crops.[20] In the United States, studies suggest that farmers could generate an additional €40 per hectare ($20 per acre) or more by harvesting corn stalks and leaves for use in biofuels.[21]

Likewise, degraded grazing lands that are not currently arable could become newly productive. Planting hearty perennials such as switchgrass and miscanthus as dedicated energy crops would permit more-extensive use of the sun, water, and soil of these lands, and also provide new economic opportunities for agricultural workers. In the United States, the potential phase-out of the Conservation Reserve Program would make millions of hectares available for re-harvesting. While it would be ecologically problematic to replant most of this erosion-prone land with annual crops, perennial grasses or trees could be a harvested on roughly 3.3–9 million hectares (8.2–20 million acres).[22]

In the European Union, non-food crops can be cultivated on set-aside land whilst receiving the standard agricultural premium. In EU-15 only, dedicated energy crops cultivated on base (not set-aside) land are eligible for a €45 per hectare payment, which makes them more attractive than some food crops. In the future, most crops, including sugar beets, are subject to greater competition as world commodity markets are liberalized.[23] (See below and Chapter 9.) In 1999, both France and Spain used over 15 percent of set-aside land to cultivate energy crops, and as reform of the EU Common Agricultural Policy (CAP) moves forward energy crop cultivation may become an even more important income support for farmers.[24]

The use of cellulosic biomass is likely to rely at least initially on existing crop residues, not newly planted acreage, because of the low cost and accessibility of this feedstock. Brazilian sugar mills, for example, have amassed large piles of bagasse (the residues left over from cane processing), and similar piles of cane leaves and tips could accrue as the practice of burning them is replaced by active harvesting of them.[25] Other likely sources for biomass in the short term are lumber mills and large agricultural processing facilities.[26] New markets for their residues could substantially increase the income of these rural industries.

While cellulosic conversion to biofuel would likely add value to low-quality wastes from forestry and agricultural processing, this could also raise prices for other industries that rely on these wastes as inputs. For example, waste-derived solid fuels, fiber products, mulch, bedding, charcoal, and composite wood could all become more expensive.[27]

8.3 Creating Agricultural Employment

By generating greater demand for agricultural products, biofuel programs have the potential to significantly increase employment in rural areas. Already, the U.S. ethanol industry is credited with employing between 147,000 and 200,000 people, in sectors ranging from farming to plant construction and operation.[28] Brazil's ethanol industry employs about half a million workers. And in the European Union, although others believe the employment effect with be smaller, a study by the Wuppertal Institute found that when biofuels reach 1 percent of the fuel supply, the industry is expected to have created 45,000–75,000 new jobs, mostly in agriculture.[29]

Research has found that the biofuel industry can generate more jobs per unit of output than the fossil fuel industry, sometimes at lower cost. The World Bank reports that biofuel industries require about 100 times more workers per joule produced than the fossil fuel industry.[30] Even Germany's relatively capital-intensive biodiesel industry generates roughly 50 times more jobs per tonne of raw oil than does diesel production.[31] In terms of job-creation costs, a study in Brazil found that a job in the ethanol industry costs 25 times less than one in the petroleum industry.[32] Since the vast majority of employment in biofuel industries is in farming, transportation, and processing, most of these jobs will be in rural communities.

In the future, biofuel programs will contribute to even greater employment, in even more countries. For example:

- *France* expects its proposed biofuel program to lead to 25,000 additional jobs by 2010;[33]
- In *Colombia*, government officials hope that a new ethanol blending mandate will add 170,000 new jobs in the sugar ethanol industry over the next several years, with each farming family increasing its average income by 2–3 times;[34]
- In *Venezuela*, an ethanol blend of 10 percent is expected to provide one million jobs in the sugar cane ethanol industry by 2012;[35]
- In *China*, officials think that as many as 9 million jobs could be created over the long term from the large-scale processing of agricultural and forestry products into liquids fuels;[36] and
- In *Sub-Saharan Africa*, the World Bank estimates that a region-wide blend of ethanol—10 percent of gasoline and 5 percent of diesel—could yield between 700,000 and 1.1 million jobs.[37]

Such massive jobs programs are achievable because biofuels production can be very labor intensive. However, it is not clear that biofuels will produce enough jobs to compensate for the losses being brought about by industrialized agriculture. Much of the early expansion of Brazil's sugar cane area, especially in the northeast, occurred as large plantation owners took over smaller-scale farms. This was a sometimes violent social disruption that led to an increase in unemployment and landlessness in the region.[38] More recently, total employment in Brazil's sugar cane industry declined from 670,000 in 1992 to 450,000 in 2003, largely because of the trend toward mechanical harvesting.[39] In the United States, despite an expanding ethanol industry, the farming population of the Midwest has been shrinking for decades, and is now one-third what it was in 1940.[40]

In developing countries, many agricultural jobs are seasonal, making it harder for workers to maintain steady employment in one area. Sugar cane in particular has an ugly history of exploiting temporary workers. To address this problem, some plantation owners in Brazil now provide laborers with off-season work, planting and preparing for the next harvest. This has helped raise the wages of sugar cane workers above those of other agricultural sectors, but the disparity between wealthy plantation owners and laborers remains striking, and subject to continuing criticism.[41]

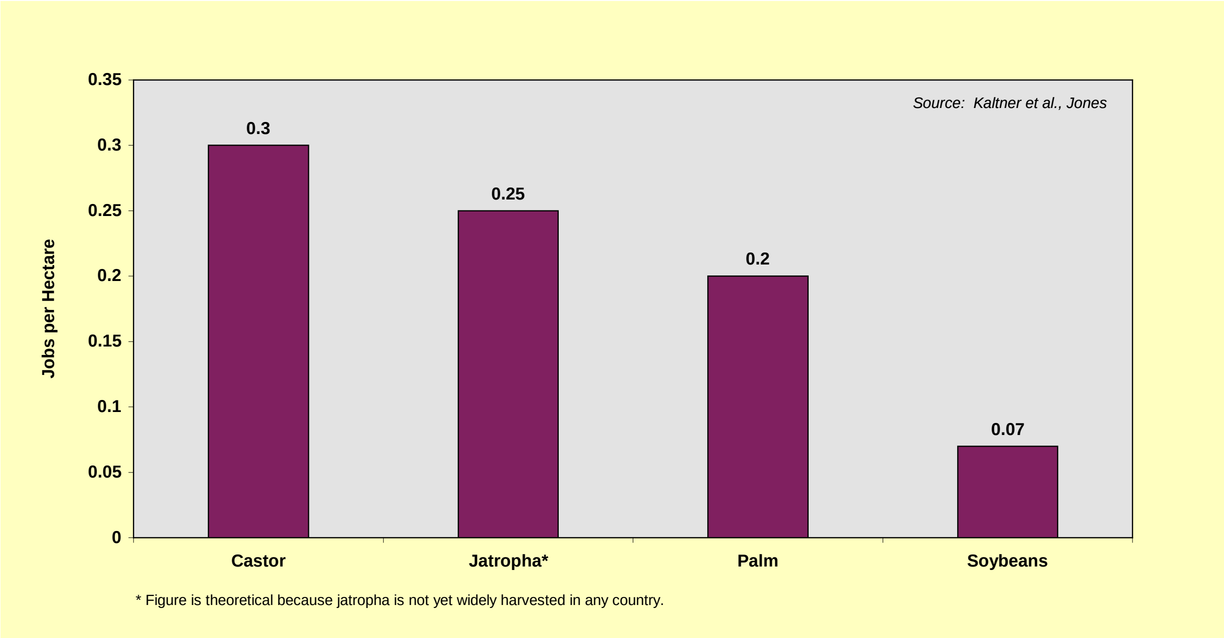
In industrialized countries, even though full-time farmers are more likely to be tending the land, they are also typically tenants rather than owners. Some 40 percent of U.S. farmers currently rent their land and facilities. As such, they are unlikely to benefit from higher corn prices—as corn prices increase, so will land renting rates—nor are they likely to have enough capital to participate in the value-adding process of converting corn into ethanol.[42]

Compared to other biofuel feedstock, labor-intensive oilseed crops in developing countries may be more amenable to sustainable and equitable job creation. Because tree oil seeds often must be harvested manually, large owners who can purchase advanced harvesting machinery have fewer advantages.[43] (See Figure 8–1 for a comparison of the labor intensity of different oileed crops in Brazil.) Moreover, since the process of converting plant oils into biodiesel is fairly straightforward and can happen at relatively low temperatures and pressures, it can often be done on a smaller scale. Thus, feedstock that is labor intensive rather than capital intensive, and the production of biodiesel rather than ethanol, may be the most promising options for supporting poor farmers and providing liquid fuel in remote areas.

Largely for these reasons, the government of India, via its National Biodiesel Program, is promoting the cultivation of oilseed plants such as pongamia and jatropha. It calculates that a jatropha farm would provide employment for 313 person-days per hectare in the first year of plantation and 50 person-days per hectare over the next 30–40 years.[44] The government of the state of Uttaranchal has already given more than 5,000 impoverished families two hectares of land to develop jatropha.[45]

Brazil's new biodiesel program, meanwhile, is focusing on castor oil and palm oil. Led by President Lula and launched in 2006, the program aims to generate employment for family farmers in the north and northeast, with the target of creating 400,000 jobs related to biodiesel production in these areas.[46] To keep the focus on poverty alleviation, rather than agribusiness, the government plans to require biodiesel producers to purchase a minimum percentage of their raw materials from family farmers (with the share varying by region).[47] So far, Lula has said there will be 350,000 people working on the biodiesel "revolution" by the end of 2006.[48] During the first three years, Brazil's government hopes that 200,000 family farms in the northeast, plus 50,000 families from other regions, will start production. It projects earnings of €178 million ($215 million) for families in the northeast.[49]

Figure 8–1. Labor Intensity of Selected Oilseed Crops in Brazil



To succeed, this and similar rural development programs will likely require extensive and continued government involvement. In Brazil in particular, large soybean farmers and processors are far better prepared than small family farmers to ramp up production of biodiesel, and soybean oil is currently cheaper than palm oil and especially castor oil.[50] Initial results from Brazil are not encouraging. Already, a huge facility that will produce biodiesel from cow tallow, which is 30 percent cheaper than soybean oil, is being constructed. When it opens, it alone could satisfy nearly 14 percent of the country's national B2 mandate (for 2 percent biodiesel blended with 98 percent diesel).[51] In the northeast, where there is no legal guarantee that smaller-scale castor oil producers will benefit from the profits available downstream in the biodiesel market, small farmers are already selling their oil to middlemen at 25–30 percent below the market price.[52]

8.4 Substituting for Agricultural Subsidies

As described in Chapter 7, a key problem for agricultural regions in the developing world is the surplus production of food crops in industrialized countries. Subsidies and gains in agricultural productivity have helped farmers boost their crop yields faster than the demand for food has increased.[53] Government supports such as deficiency payments make it economical for industrial farmers to continue overproducing and then dump their excess product onto the world market at prices well below the cost of production. While this dumping has marginally benefited industrialized agricultural interests, it is stagnating agricultural development in poorer countries, which are far more dependent on farm incomes. Agriculture provides less than 2 percent of income and employment in rich countries, while some of the poorest countries rely on agriculture for 35 percent of their GDP.[54]

As developing countries put increased pressure on industrialized countries to eliminate or reduce these distorting subsidies, some analysts have offered biofuels as a possible solution. They propose shifting government money out of traditional agricultural subsidies and into programs designed to increase the domestic supply of biofuels. In other words, rather than sending under-priced crops abroad, industrialized countries could process them into fuels. In doing so, biofuel programs in industrialized nations could inadvertently do more to boost the agricultural economies of developing countries than biofuel promotion policies in these countries themselves.

In the United States and Europe, biofuel support programs have already acted as a de facto substitute for other agricultural subsidies, such as for rapeseed and corn. The EU's growing market for biodiesel has enabled policymakers to set aside large areas of land from food production, while also reducing international dumping and benefiting domestic farmers. In the United States, the ethanol tax credit and various state blending mandates have served to displace some amount of corn deficiency payments.[55] As the demand for ethanol has led to reductions in corn export growth, "ethanol" has surpassed "exports" as the bigger user of corn.[56]

Despite the potential for biofuels to mitigate the damage done by industrialized country subsidies, fundamental problems may remain. Even if they grow energy crops for export, farmers in less-developed countries will have a hard time breaking into the markets of industrialized countries, due to high tariffs and other trade barriers. Agricultural interests in the EU and United States are adamant that their own domestic biofuel industries be protected. In the EU, rapeseed growers are concerned about competition from palm oil growers in Malaysia and Indonesia, who can produce a much cheaper plant oil feedstock. In the United States, corn and soybean farmers are concerned about imports of sugar ethanol or plant oils from Brazil or other Latin American countries. And if industrialized countries invest heavily in nurturing a homegrown cellulosic biofuel industry, they will likely protect that industry as well, even if it is not internationally competitive. (See Chapter 9.)

8.5 Biofuel Processing: Adding Value to Agricultural Harvests

While growing and harvesting the feedstock for biofuels can bring income and jobs to rural areas, a large share of the "added" value of these fuels occurs during the conversion and production stages. As a refinement of agricultural resources, biofuel processing can be a way to bring more money to agricultural communities, giving farmers the opportunity not only to be suppliers of feedstock, but also to profit from later stages of the value chain.

In the United States, for example, the construction of a 150 million liter (40 million gallon) ethanol plant could provide 40 full-time jobs and increase the value of the corn it ferments by 10–25 percent.[57] Processing can convert €1.65 ($2) of corn into €4–5 ($5–6) worth of products.[58] Biofuel processing facilities not only provide additional jobs in rural areas, they also tend to elevate the prices of nearby crops—by reducing the land area available for these crops and making supplies tighter.[59]

Biofuel processing work tends to pay better than feedstock production, with refiners generally receiving higher wages than typical agricultural laborers. In Brazil, because ethanol production requires more technical skill, these "value-adding" workers are paid about 30 percent more than laborers involved in cane harvesting. In the center-south of Brazil, sugar milling and ethanol fermentation together provide nearly 40 percent of the jobs in the sugar-ethanol industry. Ethanol production provides nearly half of these jobs.[60]

8.5.1 Co-products

Facilities that convert agricultural products into fuels can benefit from the production of "co-products" as well, further boosting agricultural incomes and the economic viability of biofuel production plants. Some of these co-products are valuable to neighboring agricultural interests: in the United States, for example, dried distillers grains with solubles (DDGS), a high-protein residue from ethanol production, provides a useful feed for cows and pigs. For feedstock like jatropha, which is poisonous to eat, the seed cake can make a useful fertilizer. And the utilization of bagasse (sugar cane residues) as energy in Brazil played a key role in keeping the ethanol industry profitable after the government withdrew subsidies in the early 1990s. Since then, large surpluses of bagasse have been a lure for other industries seeking a cheap source of energy.[61]

Other byproducts are less useful to the agricultural community, but foreshadow future "biorefineries" that promise to add even greater value to raw agricultural products. (See Chapter 5.) Glycerin, a byproduct of biodiesel production, can be a useful chemical feedstock for soaps, cosmetics, lubricants, and pharmaceutical products. Similarly, ethanol can become ethylene, which is among the most important petrochemical intermediate, contributing to the production of a wide range of chemicals, fabrics, and plastics. However, it should be noted that the abrupt expansion of biofuel production can create a market glut for the co-products, as has happened with glycerin in Europe, reducing their price and undercutting their ability to benefit rural economies.[62]

Existing ethanol "wet mills" in the United States are already rudimentary biorefineries, producing not just ethanol fuel but also high-protein feeds, high fructose corn syrup, sugars for chemical feedstock, and a range of other products. Facilities that produce bio-based products may in the future resemble petroleum refineries, where fuels comprise the bulk of production but materials and chemicals provide a disproportionate amount of the profit. (See Chapter 5.)

8.5.2 Indirect Benefits to Rural Communities

In addition to the direct benefits derived from biofuel harvesting and processing, the creation of new biofuel industries can bring indirect benefits to rural communities. For instance, all the construction required to build a new biofuel producing facility—a corn ethanol mill, or a biodiesel transesterification plant—can bring a significant one-time boost to the local economy. About as many jobs are produced during the construction phase of an ethanol plant as during its operational phase, and the plant will also require routine maintenance.[63] Additionally, transporting feedstock to the facility and shipping fuels and co-products from the facility can generate extra business for local trucking or rail companies.

Perhaps the biggest multiplier of biofuels, both economically and socially, is the additional money spent by members of the community, who gain new or higher-paying jobs. People buy their basic necessities near where they live; they find local places to buy food, clothes, tools, or entertainment; and they pay taxes and contribute to the development of a community. In this realm, biofuel production facilities that are locally owned tend to bring greater local benefits. Farmer-owned enterprises cause more money to circulate in the local economy than traditional cooperatives or corporations owned by city-dwelling stockholders.[64] Workers at ethanol facilities located in smaller communities seem also to support more jobs in their region.[65]

8.6 Biofuels for Local Use

While biofuel production and processing promise many potential benefits, one of the most direct benefits that biofuels can provide rural communities is the fuel itself. Especially in places that are vulnerable to disruptions in the supply of refined petroleum fuels, biofuel can be a more reliable alternative. It can be appropriate both in industrialized countries and in the developing world.

As early as 1906, a senator from the U.S. state of North Dakota dreamed that a new tax reduction on ethanol would mean “every farmer could have a still” to supply heat, light, and power at low prices.” More recently, Germany’s deputy minister of agriculture has collaborated with John Deere & Co. to produce a tractor that farmers could run on their own rapeseed oil.[66] Oil seeds grown in inland parts of Brazil could help farmers avoid the high cost of diesel, which must often be delivered deep into the country over low-quality roads.[67] In Argentina, some industrial farmers have calculated that homegrown biodiesel can cost half the pump price of fossil diesel.[68] Such homegrown fuel production is reminiscent of the old “oat model,” whereby farmers grew food for their draft animals.

In more isolated regions, biofuels make particular sense as an alternative to petroleum fuels that must be imported via a long, vulnerable supply line. Many regions have little infrastructure for distributing fuels via train or pipeline. They are particularly dependent on the liquid fuels that trucks can bring over poorly maintained roads, and the price of these imported fuels can be several times higher than the prices seen at fuel depots in the industrialized world. (See Chapter 7.)

Remote rural communities typically depend on imported liquids fuels for applications other than transport, such as heat and power for cooking, lighting, and industry. Here, liquid biofuels can play an important role as non-transportation fuels. The World Bank’s Millennium Gelfuel Initiative, for example, seeks to promote ethanol stoves as an improvement over stoves that use diesel, kerosene, liquid petroleum gas, and conventional fuel wood. In a complementary but insofar limited effort, the Bank has designed a prototype facility that can process sugar cane and sorghum into ethanol, electricity, biogas, and cattle feed.[69] In Brazil, organizations including Winrock International are beginning to promote an adapted version of this to help remote areas extract high-quality energy from sugar cane.[70]

Other places are using fuel from oilseed crops. In Mali, the Mali-Folkecenter has facilitated the planting and processing of jatropha trees near villages, to spare them the cost of importing expensive fossil diesel.[71] (See Sidebar 8–1.) Senegal, too, is in the process of pilot testing an innovative rural multi-energy service delivery vehicle based on direct vegetable oil from jatropha.[72] Similar projects are under way in communities around the world. In many places, the oil seeds are ready to be harvested, and people lack crushers that would more efficiently extract the oil.

Since fuel wood collection and cooking are often the responsibilities of women, new “modern” biomass initiatives can benefit them in particular, saving many hours of fuel gathering and reducing unhealthy levels of smoke indoors.[73] In Tanzania, community groups distributed jatropha oil lamps and cooking stoves to women in the village of Milmani, which soon raised more than 30,000 jatropha seedlings, which they will soon be able to exploit as a new reserve of fuel.[74]

Sidebar 8–1. Village-Scale Jatropha Oil Harvesting for Biofuel

In Mali, only 12 percent of the country's 12 million residents—and just 1 percent of the rural population—has access to electricity. But biofuels could change that. Equipped with seed crushers, Malian women have increased their social standing by extracting a biofuel that burns cleaner than diesel, arrives more predictably, and keeps more money in the local community. Jatropha bushes grow well on marginal lands in arid areas, can be harvested twice annually, and remain productive for decades. And the oil from their seeds can be used to fuel generators and vehicles, and provide heat for cooking. Because diesel fuel represents an estimated 50 percent of the total costs of operating diesel engines, substituting jatropha oil can save communities significant amounts of money and provide energy for many people who otherwise would go without.
Source: See Endnote 71 for this chapter.

Cellulosic fuels, which can be co-harvested with feedstock for liquid biofuels, offer promise for local energy as well. Sugar cane bagasse is already burned on a large scale for industrial processing of sugar and ethanol in Brazil, Mauritius, and Hawaii, among other places. Increasingly, bagasse is seen less as a waste product and more as a good source of electricity, to be sold to the grid or used locally.[75] In China, grain stalks are widely harvested for energy, and in both China and India, wet organic wastes are commonly digested into biogas. Through such efforts, rural communities can begin harnessing a greater amount of local biomass energy now, before waiting for technologies that convert cellulosic matter into liquid form.

8.7 Industry Concentration and the Distribution of Profits

At their best, biofuel programs can enrich farmers by helping to add value to their products. But at their worst, biofuel programs can expedite the very mechanization that is driving the world's poorest farmers off their land and into deeper poverty. Most likely, the biofuel economy of the future will be characterized by a range of production types—some dominated by large, capital-intensive businesses, some marked by farmer co-ops that can compete with large companies (and are protected by supportive policies), and some where biofuels are produced on a smaller scale and used within the rural communities themselves. Regardless of the scale of production, however, one thing is clear: the more involved farmers are in the production, processing, and use of biofuels, the more likely they are to benefit from them.

8.7.1 Local Ownership and Small-Scale Production

Studies show that rural communities benefit considerably more when farmers themselves have a stake in the refining stages of biofuels production. In the United States, for example, farmers benefit 5–10 times more from the presence of a corn ethanol mill when they are part owners.[76] Yet historically, farmers have not been the owners of agricultural processing facilities: large processors, with considerable financial capital, have received most of the profits from value-added commodities. In the United States, for every dollar spent on food, the share of the final market price going to farmers dropped from nearly 33 euro cents (40 U.S. cents) in 1910 to 6 euro cents (7 U.S. cents) in 1997.[77] A typical corn farmer receives less than 10 percent of the price of corn flakes, while a wheat farmer receives just 6 percent of the price of bread.[78] Farmers have been squeezed by increasingly concentrated oligopolies at all levels of the industry—seed growers, chemical refiners, machinery manufacturers, food processors, and grocery retailers.[79]

As agricultural commodities are refined into higher value products, international tariffs increase. This hinders market access for value-added exports from developing countries, and has prevented farmers in the poorest regions from participating in more profitable agricultural processing.[80]

To help small-scale farmers benefit in the biofuel economy, some governments have enacted policies to ensure that they too see profits from fuel production. In Brazil, small growers, who own about 30 percent of the sugar cane land area, negotiate a revenue-sharing agreement each year with the plantation owners, who own the remaining land area as well as most of the sugar/ethanol mills.[81] Similarly, the U.S. state of Minnesota has sought to favor smaller producers and farmer-owned cooperatives. Starting in the late 1980s, the state provided a special producer payment of 6.5 euro cents per liter (20 U.S. cents per gallon) for the first 57 million liters (15 million gallons) produced by an ethanol mill. As a result, 12 of the state's 14 ethanol mills were formed as farmer cooperatives, and farmer-owned ethanol cooperatives now produce about 40 percent of the ethanol sold in the United States.[82]

Seeking to emulate the success of Minnesota's program, policymakers in Saskatchewan, Canada, have approved a biofuel program that requires distributors to purchase up to 30 percent of their ethanol from small producers—approximately 25 million liters per year.[83] In the private sector, a Colorado-based company called Blue Sun Biodiesel has worked toward the same end: farmer ownership in biofuel production facilities. By providing farmers a guaranteed market for their crop, plus additional profit for the sale of biodiesel, Blue Sun persuaded farmers near Denver to invest $5,000 (€4,132) each in the enterprise and switch some of their crop to rapeseed.[84] So far, the company is successfully supplying school buses, city buses, and delivery trucks with locally produced biodiesel, and the entrepreneurs are now spreading their model to New Mexico.[85] Through such programs, small growers can collaborate to receive substantially more income for their crop each year.

It is often assumed that stringent environmental or social standards will act as barriers for developing countries to enter industrialized country markets. (See Chapters 9 and 18.) However, contract farming in Africa has provided a steady source of food products to the European market. In Madagascar, the use of "micro-contracts" and the provision of support and supervision to small farmers have resulted in higher welfare for farmers, greater income stability, and shorter lean periods. Furthermore, improved techniques for resource management and technology transfer have had positive spillover effects for the production of rice, the staple crop.[86] The possibility exists for agricultural extension services and other policy institutions to use biofuels as a tool for sustainable agricultural development and poverty alleviation in conjunction with the production of biofuels for domestic use or export.

At the same time, rising interest in organic and environmentally sustainable production of biofuel feedstock may also boost rural economic benefits, by contributing to increased labor intensity in agricultural production.

8.7.2 Industry Consolidation and Large-Scale Production

Despite well-meaning efforts to encourage small-scale biofuel production in many countries, larger-scale owners and corporations will likely still dominate the future biofuel industry. As with many industrial activities, significant economies of scale can be gained from processing and especially distributing biofuels on a large scale.

Brazil, for example, is seeing increasing consolidation in its sugar ethanol industry as the largest domestic entities, Cosan and Copersucar, grow, and as companies from Europe, Japan, and the United States invest in Brazilian mills. According to some estimates, in the coming years the industry may be controlled by only 6–7 larger groups, compared with about 250 millers today.[87] Even Brazil's embryonic biodiesel economy is dominated by five main producers, one of which, Agropalma, produces more than half of the total output.[88] Dedini, which has built 80 percent of Brazil's ethanol distilleries, is also the primary builder of the country's biodiesel facilities.[89]

In China, five provinces—Jilin, Heilongjiang, Henan, Anhui and Liaoning—have been using ethanol blends since 2000, primarily to help alleviate the burden of grain surpluses on farmers. However, the country's nascent biofuel industry is comprised by just a few, very large ethanol plants, and the extent to which the value-adding benefits have reached rural communities is not clear.[90]

In the United States, concentration in ethanol production has fluctuated over the years, though it appears to be again headed in the direction of greater consolidation. In the early 1980s, federal loan guarantees spurred the construction of hundreds of tiny ethanol facilities, but only the largest companies were able to survive competition from low oil prices in the mid-1980s. By the end of the decade, a single company, Archer Daniels Midland (ADM), was producing nearly 80 percent of the country's ethanol.[91] Since then, cooperative programs such as Minnesota's have encouraged the construction of jointly owned ethanol mills, such that by 2005, more than half of all ethanol mills were farmer owned, and ADM's market share had shrunk to only about 25 percent.[92] However, about three-fourths of the ethanol plants being constructed in 2005 were not farmer owned, and several large companies, including ADM, have announced plans to increase their capacity dramatically by building larger facilities.[93]

Cargill, an international agricultural processor, is currently building a huge biodiesel plant in the United States with a capacity of 189 million liters (50 million gallons), large enough to nearly double the country's 2004 biodiesel production. Simultaneously, Cargill is building large soybean oil production facilities in Brazil and constructing dehydration plants to facilitate imports of Brazilian ethanol to the United States, via Central America and the Caribbean (regions that enjoy preferential trade status).[94] The largest current U.S. biodiesel distributor, World Energy Alternatives, distributes half or more of the biodiesel in the country and is a subsidiary of Gulf Oil.[95]

Even in Europe, where companies often run under tightly controlled licenses, large producers and distributors threaten to dominate the "value-adding" component of the biofuels industry. ADM is building large biodiesel facilities in Europe as well, where it is already the second largest biodiesel manufacturer.[96] And in 2005, the EU approved a joint venture between Bunge and Diester, creating the largest biodiesel marketer on the continent.[97]

8.7.3 Concentration in the Cellulosic Biofuel Industry

The next generation of biofuel production facilities will create a market for far greater amounts of agricultural biomass and promises to create even higher value co-products, further helping rural communities. However, it will also require the development of more capital-intensive production facilities, which could add to the advantages that large companies demonstrate in biofuel production.

The promise of refining previously low-value biomass into boutique fuels and products has already attracted wide-ranging corporate interest. Some companies currently involved in ethanol fermentation hope to become leaders in developing new refining technologies—including Dedini, which is developing a process to hydrolyze and ferment sugar cane bagasse in Brazil, and the enzyme companies Novozymes and Genencor.[98] Other companies are relative newcomers to the field, such as chemical manufacturers Dow and Dupont, both of which have launched efforts to produce a wider variety of biomaterials.[99]

Oil and auto companies are making investments to pioneer the next generation of biofuels as well. Shell, already involved in biofuel distribution around the world, has invested in the first facilities to demonstrate both enzymatic hydrolysis (with PetroCanada) and gasification of cellulosic matter (in Germany). It has also conducted significant research into a process that can pyrolyze wet biomatter into a liquid fuel. And auto companies Volkwagen and DaimlerChrysler have partnered to develop a large jatropha plantation in India and are working with Shell on its German demonstration gasification-to-liquid facility. (See Chapter 5.)

These corporate investments signal that a new “bio-economy” may indeed sprout in the coming decades. It also points to the possibility that still larger companies may enter the rural economy to put the squeeze on farm incomes. If so, the real profits are likely to go not to those who can produce large quantities of biomass feedstock, but to those with the proprietary technology that can ply this feedstock into fuels and products.

8.8 Food vs. Fuel

When considering rapid increases in biofuel production, there is a concern that crops that would otherwise become food might instead become fuel, leaving the world’s poorest inhabitants hungry. This concern is important; however, it may be too simplistic. Not only will greater demand for certain crops increase their production, but such demand could bring particular benefits to farmers, who comprise many of the world’s poor. While biofuel programs could raise food prices and contribute to hunger, they could also help address the root of world hunger: poverty.

So far, biofuel production has indeed raised the price of certain foods. For example, biodiesel production in Europe has led to an increase in the price of rapeseed oil, and sugar ethanol production in Brazil has contributed to a rise in the global price of sugar. Such increases in the demand for and price of food crops have been a deliberate and fundamental motivation of biofuel programs, as governments aim to protect farmers from excessively low prices. (See Chapter 7.)

Higher crop prices will not necessarily harm the poorest people. More likely, as with most enterprises, some people will be hurt and some will be helped. While urban slum dwellers are unlikely to benefit from biofuel programs, many of the world's 800 million undernourished people are farmers or farm laborers, who could benefit.[100] Moreover, if biofuel programs end up absorbing much of the surplus crop production in industrialized countries, they could spare farmers in the developing world from commodity “dumping” and artificially low prices.

Poor farmers are more likely to benefit if biofuel production is done in a small-scale, labor-intensive manner—one that keeps them employed and able to afford food. The alternative is large plantations of monocultures controlled by wealthy producers, who could drive farmers from their land without providing new opportunities. In Brazil, where the early years of the Proálcool program did lead to regional food scarcities in the northeast, the government's current embrace of biodiesel is specifically targeted at poverty reduction.[101] By providing families of laborers with a new market for their tree oil crops, the government aims to improve the economic conditions that would otherwise lead to hunger.

In the future, markets for cellulosic biofuel feedstock offer a promising opportunity to relieve food supplies from direct competition with biofuels. Farmers could preserve the sugary, starchy, or oily components of the plant for food and sell the fibrous components as fuels. By adding value to agricultural residues, farmers may even be able to benefit while also selling food at a lower price.

Yet even cellulosic feedstocks can put pressure on food supplies, particularly if enormous demand for biofuels strains the limits of agricultural potential and productive land. The likelihood of such tension will depend on a variety of factors, including the ability of agronomists and farmers to further raise agricultural yields, the overall size of the human population, the extent to which calorie-intensive meat and dairy products dominate diets, and the fuel efficiency of peoples' lifestyles. (See Chapter 6.)

These factors notwithstanding, the central cause of food scarcity in the world today is and will likely remain economic inequality and inadequate food distribution.[102] Since the very poorest people are unable to afford food when prices are set by wealthier consumers, the most immediate question is whether biofuels will help to reduce some of these inequalities.

8.9 Conclusion

Continued expansion of biofuel production will increase global demand for agricultural products and result in the creation of new jobs at every stage of the production process, from harvesting, to processing, to distribution. As more countries become producers of biofuels, their rural economies will likely benefit as they harness a greater share of their domestic resources.

But not everyone will benefit equally. Of all the participants in the biofuel economy, agribusinesses are most assured to profit, since mechanized harvesting and production chains are the easiest option for rapidly scaling up biofuel production. Large-scale agricultural processors and distributors will be responsible for supplying most of the refined fuels as well. The development of cellulosic conversion technologies will only further exaggerate the advantages of those interests with large pools of financial capital. But the current expansion of biofuel production offers a unique opportunity for policy makers to avoid some of the pitfalls of existing food industries.

As policymakers proceed with biofuel programs, they will need to decide to what extent they want to encourage small farmers or laborers to share in the profits. If this is a priority for governments, then policy options include well-enforced labor standards and profit-sharing agreements, possibly using existing models in the states of São Paulo in Brazil and Minnesota in the United States. On the processing side, governments can support smaller-scale producers and farmer cooperatives by requiring fuel blenders to purchase their fuel from them at fair prices.

When considering biofuel programs for their capacity to promote rural development, decision makers in industrial countries must remain mindful of just how important agriculture is to the economies of the developing world. Advocates of rural development at home might consider to what extent they also care about development in other countries that face similar challenges in their agricultural sectors. Restrictive tariffs can benefit rural communities in industrialized countries while harming those in less wealthy countries. At the same time, should industrialized countries begin importing biofuels from developing countries, it may be difficult to enforce international labor standards.

A biofuel industry that is locally oriented—in which farmer-owners produce fuel for their own use—is more likely to guarantee benefits to a rural community. In these situations, farmers may risk bad seasons and poor harvests, but, by adding value to their own products and using these goods locally, they are also less vulnerable to external exploitation and disruptive market fluctuations. Although liquid fuels produced at home are often used for cooking or electricity, rather than transportation, it is worth noting that readily available technologies to convert "modern" biomass into energy promise to be a more directed way to alleviate poverty, especially in more remote, oil-dependent regions.

Chapter 9. International Trade in Biofuels

9.1 Introduction

The current international trade in biofuels is quite small when compared to trade in fossil fuels such as petroleum and natural gas. However, biofuel production is expected to more than double in the coming decade as new government and industry policies promote greater use of renewable energy sources and as the global demand for liquid fuel rises. Growing interest in a wide variety of biomass resources, many of which are underutilized in much of the world, is likely to foster new trading relationships.

The greatest demand for biofuels is concentrated in industrialized regions that consume large amounts of energy, such as the United States, European Union (EU), and Japan, as well as in rapidly industrializing nations like China and India. The largest potentials for producing these fuels, meanwhile, are found in the tropical countries of South America, sub-Saharan Africa, and East Asia, and in Eastern Europe.[1] Trade is a natural outgrowth of such imbalances.

As more countries explore biofuels as an energy source, the costs of meeting energy needs with regionally available feedstock may guide countries' decisions to trade biofuels internationally. In general, the decision to facilitate trade in these fuels must be balanced with domestic and regional energy needs; large-scale production for export should not preempt the development of smaller-scale biofuels production for local use.

This chapter discusses the main risks and opportunities associated with international trade in biofuels. It describes the current status of this trade and explores the key barriers to its expansion in the future, including tariffs, lack of international fuel quality standards, concerns about environmental and social standards, and a poorly developed market. It also considers biofuel trade in the context of the wider international trading regime.

9.2 Current Biofuel Trade

Today, biofuel trade occurs mainly between neighboring regions or countries, though it is increasingly happening over longer distances. Brazilian ethanol is now exported to Japan, the European Union, and the United States; Malaysia exports palm oil to the Netherlands and Germany; and Canada exports wood pellets to Sweden. This is happening despite the bulky and lower calorific value of most biomass raw material.

9.2.1 Trade in Ethanol and Related Commodities

Only about 10 percent of the ethanol produced in the world today is traded internationally.[2] Historically, most of this trade has been for non-transportation uses—as a base for alcoholic beverages, as a solvent, and for other industrial applications. However, fuel ethanol is becoming an increasingly popular global commodity as oil prices rise and as governments adopt new policies promoting biofuel use.

Ethanol produced from Brazilian sugar cane accounts for the vast majority of liquid renewable fuel traded today. In 2004, Brazil was the world's dominant ethanol exporter, accounting for approximately half of total global trade, for all uses.[3] The main recipients of these exports are India, the United States, South Korea, and Japan.[4] (See Table 9–1.) Some Brazilian exports also flow into the United States indirectly via Central America and the Caribbean, where ethanol is processed and can enter tariff-free under the Caribbean Basin Initiative, a regional preferential trading program.

Table 9–1. Brazilian Ethanol Exports, All Grades, 2004

Importing Country	Exports[a] (million liters)
India	475
United States	426
South Korea	239
Japan	209
Sweden	198
Netherlands	156
Jamaica	133
Nigeria	106
Costa Rica	106
Others	361
Total	2,447

Note: Figure includes fuel, industrial, and beverage uses.
Source: See Endnote 4 for this chapter.

Several other producer countries, including the Pakistan, the United States, South Africa, Ukraine, and countries in Central America and the Caribbean, also contribute to ethanol trade, though their relative exports compared to Brazil are quite small. Due to preferential access to the European market, small amounts of ethanol are shipped from Africa and Asia to Europe. Pakistan has historically been the largest exporter of ethanol to the European Union.[5]

Most of the ethanol traded today is pre-processed ethanol, manufactured in the country where the feedstock is grown, because it has generally not been economical to transport feedstock long distances for ethanol production. However, some corn from the United States is transported to Canada for ethanol production. In the future, the transport of some cereals for ethanol production may takeplace. Notwithstanding, as sugar is currently the cheapest feedstock, many low-cost producers of sugar cane in Africa, Latin America, and Asia plan to increase their share in global ethanol trade. (See Chapter 7.)

Future ethanol trade will be driven in large part by countries that are not necessarily interested in developing domestic biofuel production, but have a desire to use biofuels to reduce oil dependence and meet carbon emissions targets under the Kyoto Protocol. Likewise, national initiatives to stimulate greater energy independence, boost rural incomes, and support environmental and socially responsible fuel production and use may have marked effects on international biofuel trade. Japan, for instance, was the fourth largest market for Brazilian ethanol in 2004. In 2005, Brazil’s leading oil company, Petrobras, and Japan Alcohol Trading Co. launched a joint venture, Nippaku Ethanol KK, to import ethanol into Japan.[6] To accommodate forecasted shipments of 25 million liters (6.6 million gallons) a month, Petrobras will invest €279 million ($330 million) over the next five years in developing the requisite export infrastructure.[7] Other biofuel-producing nations may develop similar relationships to facilitate trade in ethanol and other fuels.

9.2.2 Trade in Biodiesel and Related Commodities

At present, there is no significant international trade in biodiesel. Germany is the world's largest producer of the fuel (from rapeseed), but this is mainly for use domestically and within the EU. This leaves considerable potential for lower-cost producers to enter the market, including major oilseed producing countries. Of the seven major oilseed crops, just two—soybeans and palm—account for 85 percent of global oilseed exports.[8] The largest soybean producer and exporter is the United States, followed by Brazil, Argentina, and China.[9] The largest palm oil producers are Malaysia and Indonesia.

Trade in biodiesel produced from palm oil is projected to increase in the coming years. Both Malaysia and Indonesia have plans to export the fuel to the EU, and Malaysia is also planning exports to Colombia, India, South Korea, and Turkey.[10] To satisfy both international and domestic demand—Malaysia aims to substitute all domestic diesel with palm based biodiesel by 2008—three new plants are due to begin operation in 2006, producing 100,000 tonnes of biodiesel annually.[11] And the international energy trading company EarthFirst Americas plans to import palm-based biodiesel into the United States from Ecuador, at a quantity equivalent to half the projected U.S. production of 200 million liters in 2007.[12] This rising trade in palm oil products has raised substantial concerns about forest loss and environmental degradation in producer countries, however.[13] (See Chapter 12.)

Despite its smaller share of the global market, it appears that the international biodiesel market may also expand rapidly in response to growing global demand. Although Europe currently manufactures more than 90 percent of the world's biodiesel, both industrialized countries (the United States) and developing nations (Ecuador, Indonesia, and Malaysia) are building infrastructure to supply regional and international biofuels markets, driven by the need to assure a secure fuel supply and reduce dependence on imported oil. (See Chapter 7.)

9.3 Competitive Advantage and the Biofuels Trade

As noted earlier, many developing countries have a competitive advantage in biofuels production due to lower land and labor costs, warm tropical climates, and a longer growing season. This makes producing biofuels for export a more cost-effective proposition for these countries compared with many industrialized nations. In Brazil, ethanol produced from sugar cane is currently competitive with fossil fuels, at 11.2 euro cents (13.6 U.S. cents) per liter. Several other developing countries have similar costs for ethanol production, including Pakistan, at 12 euro cents (14.5 U.S. cents) per liter, and Swaziland and Zimbabwe, at costs close to Brazil's. All of these nations currently export ethanol to the EU.

Some developing nations that currently produce biodiesel for the domestic market have plans to expand their export potential, including Malaysia, Indonesia, and the Philippines. Many countries in Central and Eastern Europe also have the potential to produce cheaper biofuel feedstock (such as wheat or rapeseed), being at a competitive advantage due to low labor costs and high resource availability.[14]

Brazil, Germany, the United States and others all have fairly well developed biofuel industries with advanced technologies for biofuel processing. As biofuel production begins to increase in other countries, these nations will benefit from expanding markets for their technologies. (See Chapters 16 and 20.)

Biofuels have great promise to provide local energy and substitute for costly oil imports, particularly in those countries that can produce them most cost effectively. But the economic and rural development benefits of producing these fuels in large quantities for export must be weighed against the environmental costs of this production. In general, the fossil energy required to produce ethanol from sugar cane, and biodiesel from palm oil, is lower than that for ethanol or biodiesel produced in Europe, and their corresponding emission reductions are greater. However, this is not the case when virgin forests are razed for biofuel production, as is happening in parts of Southeast Asia. Trade in biofuels is advantageous from a cost and greenhouse-gas minimizing perspective *only if it is cultivated on already established agricultural or set-aside lands, or on degraded lands poorly suited for traditional agriculture*.[15] (See Chapters 11 and 12.)

Although developing countries consume much less energy overall than industrialized countries, their demand for liquid fuels is increasing rapidly. This raises the question of whether biomass fuels should primarily be used locally or exported—and whether market forces should have the final say. Brazil, for example, is planning to increase its ethanol production dramatically over the next eight years, and it is beginning to produce biodiesel from soybeans, castor and palm oil. Only a fraction of this will be exported. For most countries, the main drivers determining this choice will be the relative prices of petroleum fuel versus plant oils and ethanol on the international market, as well as incentives offered for the production of renewable fuels. In general, it would be more rational to use biofuels locally and export only the excess—bearing in mind that international competition will force domestic producers to be more competitive.

9.4 Policies Affecting International Biofuel Trade

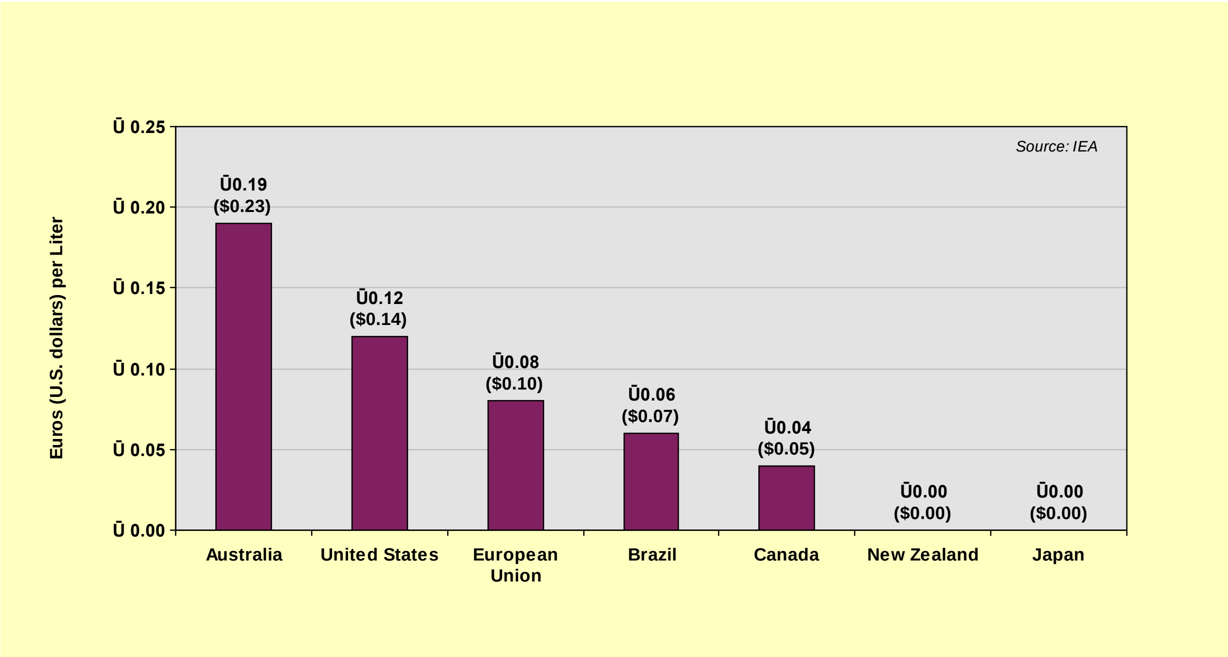
Some countries with large agricultural sectors have shown resistance to opening their markets to foreign biofuel imports. These policies create barriers for many producers in developing countries that wish to significantly expand their production and export of biofuels in the coming years. Policies in the form of tariffs that keep developing country commodities out of industrialized markets, or subsidies that support industrialized country biofuel producers, may be equally discouraging for market entrants.

However trade agreements have great potential to increase the global penetration of biofuels into fuel markets. Industrialized countries grant developing countries market access or negotiate trade agreements that lower barriers to trade in biofuels and related commodities to encourage the latter's economic development and benefit domestic consumers. The future of biofuel trade will be affected by these changing trade policies, especially current negotiations on the production and trade of agricultural products.

9.4.1 Tariffs Policies Affecting Biofuel Trade

The EU, United States, and Australia are among the large agricultural exporting economies that have imposed import duties and other restrictions on foreign ethanol and biodiesel and their agricultural inputs.[16] (Figure 9–1.) Simultaneously, the EU and United States both offer preferential market access to developing countries by way of unilateral tariff reductions that encourage imports of certain agricultural commodities and biofuels.

Figure 9–1. Ethanol Import Duties in Selected Countries, 2004



Ethanol is taxed at varying rates depending on its intended use. In the European Union, the import duty for un-denatured (pure) alcohol is €0.19 per liter, while for denatured alcohol (ethanol with additives), it is €0.10 per liter.[17] Despite the differing tariff rate, both denatured and undenatured alcohol is imported under customs classification 2207 in Europe, making it difficult to identify how much ethanol is used for fuel production. Only fuel ethanol that is pre-blended with gasoline is classified separately under heading 3824 and charged a normal customs duty of around 6 percent.[18] In the United States, ethyl alcohol is classified under the agriculture chapter and again under chapter 99 for fuel-grade ethanol. The United States, taxes ethanol imports at €0.15/$0.18 per liter (€0.44/$0.54 per gallon).[19]

Biodiesel imports are also taxed at varying rates, due in part to the different feedstock options. Global trade in whole oilseeds, particularly soybeans, is relatively unrestricted by tariffs and other border measures; however, oilseed meals, and particularly vegetable oils, have higher tariffs. For soybean oil, tariffs average around 20 percent, while tariff rates for whole soybeans are generally around 10 percent.[20] In the EU, plant oils for biodiesel face low or no tariffs. For biodiesel in the form of fatty acid methyl ester (FAME) imported from the United States, a non-member state duty of 6.5 percent applies, and there are no quantitative restrictions. In addition, these conditions apply only to the import of the biodiesel (FAME) itself, not to the import of source products like tallow or used cooking oil. Rules and tariffs governing straight vegetable oils (SVO) are separate and specific because of the potential for these oils to enter into food production.

Under the Caribbean Basin Initiative (CBI), the United States exempts from import tariffs some degree of ethanol from Central American countries and the Caribbean—specifically, imports produced from foreign feedstock that equal up to 7 percent of the previous year's U.S. demand.[21] CBI countries have never come close to meeting this ceiling; in the past five years, CBI exports as a share of U.S. production have hovered around 3 percent.[22] CBI countries also may import feedstocks or fuel (e.g., from Brazil) for export to the United States, as long as 35 percent of the value of the product is produced in a CBI country.[23]

The Central American Free Trade Agreement (CAFTA) will supercede CBI when it takes effect for countries that are party to it, potentially including five Central American countries and the Dominican Republic. Like CBI, it will allow continued tariff-free exports through CAFTA countries for ethanol produced by non-CAFTA and non-CBI countries, such as Brazil, up to the 7 percent cap of total U.S. production.[24] All other ethanol produced by CAFTA, or CBI country feedstock, can be imported tariff-free. CAFTA was supposed to take effect in January 2006 but has been delayed due to unresolved legal issues, including pending approval by some legislatures in Central America.[25]

In Europe, the EU grants special trading preferences to Africa, Caribbean, and Pacific (ACP) countries. The EU also has a General Systems of Preferences (GSP) that encompasses all developing nations. This agreement granted tax preferences for ethanol from 12 countries as a part of an anti-drug regime had duty free access for ethanol to the EU Market until 2005.[26]

Countries under the so-called Everything But Arms (EBA) initiative are exempted from EU duties on ethanol (and all other exports, except for sugar, rice and bananas that will be covered by exemptions from 2009 on). Under this agreement, significant (though erratic) exports come in from the Democratic Republic of Congo, varying from 86,000 liters in 2003 to 19,000 liters in 2004.[27] Altogether, biofuel imports into the EU under preferential trading arrangements nearly doubled between 2002 and 2004, to 3.1 billion liters.[28] (See Table 9–2.)

Table 9–2. Biofuel Imports Into the EU Under Preferential Trading Arrangements, 2002–2004

Trade Agreement	2002	2003	2004	Average 2002–04	Share of Total Biofuel Trade 2002–04
	(million liters)				(percent)
GSP normal	227	183	288	233	9
GSP Anti-Drug preference	553	1,569	1,413	1,178	47.5
ACP	291	269	155	238	9
EBA	30	86	19	45	1.5
Others	107	104	123	111	4
Total preferential	1,208	2,211	1,998	1,805	70
Total MFN	657	495	1,125	759	30
Grand Total	1,865	2,706	3,123	2,564	100

Source: See Endnote 28 for this chapter.

As a result of the GSP, Pakistan was the largest supplier of ethanol to the EU for much of the past decade, producing a range of 1.3 million to 2.1 million tons of the fuel from sugar cane during the period from 1994–2004.[29] In July 2005, however, the World Trade Organization (WTO) ruled that the EU was unevenly granting preferences to the 12 countries included under this policy. As a result, a new GSP Plus system has been designed. Under this regime, 15 countries that ratified certain international agreements on human and workers rights as well as on environment protection, were granted tax-free import preference as of January 2006. Pakistani ethanol is no longer eligible for tax reduction on its exports to the EU, a change that has caused two ethanol plants in Pakistan to close and halted plans for seven new plants. Other countries may step up to fill the gap.[30]

The EU is also in the process of conducting negotiations with MERCOSUR (the Latin American trade bloc) that would significantly lower or remove trade barriers for these countries; however, negotiations have stalled. Conclusion of a MERCOSUR agreement could allow large amounts of Brazilian ethanol to enter the EU.[31] European nations with higher production costs, such as France, Spain, and Sweden, have voiced concerns that they could be negatively affected by such a change, so some limits would likely be imposed (e.g. Tariff Rate Quotas).[32]

The relative tariff levels levied on developing country exports can largely determine the degree of success for emergent biofuel industries (over 60 percent of ethanol imported to the EU was imported tariff-free). Similarly, the quantity and placement of agricultural subsidies has a profound effect on the quantity and type of feedstock available for biofuels production.

9.4.2 Agriculture Subsidies and the Biofuel Market

Protection of domestic agricultural interests in many countries is in large part responsible for the hampering of international agricultural trade. The U.S. corn sector—the second largest player in the international ethanol market—is also the largest recipient of the nation's agricultural subsidies, receiving nearly €34.7 billion ($42 billion) in government payouts over the last ten years.[33] Similarly, the European Union's Common Agricultural Policy (CAP) contributes to one-third of the farmers' income, according to the OECD-Producer support estimate index. Before the recently introduced reform, EU sugar subsidies cost consumers and taxpayers an estimated €3.6 billion in 2004, and also compromised the competitiveness of developing countries.[34] (See Chaper 7 for more on the role of subsidies.) The redirection of export subsidies from classic agricultural commodities toward biofuels can increase the opportunities for developing countries to meet demands for biofuels as their traditional agricultural capacities are affected by changes in the structure of the world market for agricultural commodities.

Removing or reducing these subsidies could change the biofuel trade landscape. The U.S. Department of Agriculture (USDA) estimates that full liberalization of the oilseed trade (meaning both subsidy elimination and tariff reduction) would result in a 5.3 percent decline in industrialized country outputs, but a 4.8 percent rise in developing country outputs, and an overall increase in world trade volume of 11.4 percent.[35] Proposed reductions in WTO's Doha Round of trade negotiations could reduce corn and sugar subsidies and increase opportunities related to these commodity markets.

Although they are not direct subsidies, biofuel targets that ensure demand are projected to have definite effects on global trade flows. Supports via biofuel mandates for the US and EU are projected to increase EU imports of vegetable oil threefold and could cause EU wheat exports to fall up to 41 percent, and Canadian wheat and coarse grain exports would be reduced by 13 and 34 percent respectively in 2014.[36] Lower industrialized country exports due to increased demand from government mandated programs can thus create increased opportunity for developing country producers.

In preparation for likely future reductions in price supports for traditional agricultural commodities, some governments are considering leveraging their massive funds for agriculture by transforming them into subsidies for the production of renewable fuels. (See Chapter 7.) The USDA estimates that expansion in U.S. ethanol production has helped to reduce farm program costs in the United States by some €2.65 billion ($3.2 billion) by reducing food program supports, a fact that has not been forgotten in anticipation of the next Farm Bill in 2007.[37] But transferring agricultural funds to biofuels may end up subsidizing inefficient production. Under the EU sugar reform plan, sugar producers with costs well above world market prices can receive funds to convert sugar factories into ethanol plants that use either sugar beet or grain as inputs.[38]

If industrialized countries transform traditional agricultural subsidies into supports for domestic energy crop production, emerging developing country producers of energy crops will operate at a significant disadvantage. However, if these subsidies are used to develop more efficient next-generation feedstock, emerging producers could remain competitive in the near term. Additionally, subsidy schemes can be implemented to periodically reevaluate supports as products become competitive, and can be used to fund new technologies in early phases of research and demonstration.

Proposed agricultural trade reforms do include some provisions for developing countries. For instance, biofuel exports from African, Caribbean, and Pacific (ACP) countries are slated to receive continued support in the wake of contentious debate over world sugar trade at the WTO. In response to the concerns of countries receiving preferential market access about the reduction in supports to sugar producers in the EU—which have historically kept prices higher in the European market—the EU has promised to provide generous development aid to all 18 ACP countries.[39] The EU sugar reform plan ensures that the production of biofuels “derived from agricultural crops that can be used to partially replace liquid petroleum products” will not be adversely affected.[40] For energy crop cultivation for biofuels within the EU-25, sugar beet will be eligible for EU energy crop aid, worth €45 per hectare. Sugar used for the production of ethanol, as well as by the chemical and pharmaceutical industries, will be excluded from the sugar quota. As sugar reform is a major challenge not only for EU beet and sugar producers, but also for many ACP suppliers the Commission has divised an assistance scheme to respond to the diversity of situations in the different ACP countries covering a broad range of social, economic and environmental actions.[41]

Decisions that industrialized countries make with regard to shifting their own subsidies towards non-conventional crops can affect the supply of both conventional and non-conventional crops. What will happen if industrialized countries move towards subsidizing energy crops, and away from supporting conventional crops? Will prices for agricultural commodities rise, bringing potential benefits to the rural poor?[42] (See Chapter 8.) The answers to these questions will largely affect opportunities for developing country agriculturalists in both conventional agricultural commodities and biofuels export.

9.4.3 Multilateral Trade Policies

As biofuels markets expand, the international legal framework governing the flows of agricultural commodities, alcohols, and alternative energies will be central to the future of biofuels trade. Likely future reductions in agricultural trade barriers have brought increasing pressure on industrialized countries to redesign their national agricultural policies and respond to ongoing trade negotiations. In the WTO’s Doha Round of trade talks, ongoing negotiations that will be of particular importance are those covering the liberalization of agricultural trade and environmental goods and services (EGS).

Agricultural vs. Non-Agricultural Goods

A key factor in the development of future biofuel policies will be whether a biofuel will be considered "agricultural" or "non-agricultural" good under WTO agreements. If a biofuel (e.g. ethanol) is an agricultural good, its agricultural production may be eligible for so-called "green box" classification under the WTO's Agriculture Agreement, which covers subsidies for activities that encourage environmental stewardship or land conservation, among other non-trade distorting activities. However, if a biofuel is a non-agricultural good (e.g. RME), then it is subject to the Subsidies and Countervailing Measures (SCM) agreement on non-agricultural subsidies, and will not be eligible for this type of environmental exemption. The subsidies could be challenged at the WTO if not in line with SCM.[43] If a biofuel is deemed a non-agricultural good, then the question remains whether it will be treated as "environmental" good (discussed below), in which case it could receive significantly deeper tariff reductions than those applied to other non-agricultural goods.[44]

Environmental Goods and Services (EGS)

Formal talks on environmental goods and services (EGS) began in 2001 as a supplement to the more general discussions on international trade in services under the WTO. Intended to enhance the mutual supportiveness of trade and environment, these negotiations set out to reduce or eliminate tariff and non-tariff barriers to EGS. They are of particular relevance to biofuels: for instance, if materials for the construction of next-generation biorefineries were to be included on the lists of environmental goods and services, construction could be expedited because tariffs on imported technologies and equipment for biofuels and other renewable fuels could be lowered or eliminated.

Negotiations on what constitutes an environmental good are still in flux. The United States is proposing a "list approach" that is based on pre-existing lists of "environmental goods." India and other developing countries have actively opposed classifying EGS based on "Process and Production Methods" (how goods are made). Further discussion of this debate and how it applies to certification is found in Chapter 18; however, it is unlikely that PPMs will be incorporated into the definition of biofuels as environmental goods in 2006 negotiations.[45]

Nevertheless, many European countries would like to specify certain production criteria for biofuels, in particular sustainable agricultural practices such as cover cropping and practices that help retain crop residues on the ground for cellulosic feedstock.[46] (See Chapters 12 and 18.) Furthermore, classification of certain organic matter streams as biomass fuels may aid WTO classification of biofuels as EGS, though the marginal environmental gains compared to cost must be further explored. It is possible, if not probable, that in future negotiations, WTO member countries could mandate certain sustainable practices for generating inputs or other requisites for biofuels to qualify as EGS.[47]

Until such issues are addressed, importing countries may attempt to establish minimum standards for goods entering their countries. Reciprocal agreements between countries with importing and exporting relationships for biofuels are not likely to be challenged at the WTO. For wider global biofuel trade, an important step toward sustainability would be the development of objective environmental performance criteria for biofuels and relevant co-products, set out in credible international, regional, or domestic standards.[48] Such an approach is discussed in Chapter 18.

9.5 Social and Environmental Issues and the Biofuel Trade

Less prevalent in trade discussions, though a growing concern among agricultural and environmental groups, is the potential for expanded international biofuel trade to cause social and environmental harm. Like any internationally traded commodity, biofuels will have a greater impact the more widely they are traded around the globe. Here, as with many other trade related issues, effective national policies will be of critical importance, as international trade often serves to only exacerbate local problems.

The primary social and environmental concerns being raised by environmental and agriculture groups include: growing competition for land; the ecological implications of industrial crop monocultures; genetic engineering of biofuel feedstock; and exploitation of farm workers. There is also concern about lower environmental and labor standards of production in developing versus industrialized countries (so called “cross-compliance” issues). (See Chapters 12 and 13.)

Genetic engineering techniques used to boost the efficiency of crop yields and protect against insect infestations could raise particular concern.[49] In the past, India and the EU have been reluctant to accept genetically modified (GM) agricultural products into their markets (especially for human consumption), and this could influence their willingness to import biofuels from countries that allow GM crops. The Cartegena Protocol on Biosafety under the U.N. Convention on Biological Diversity allows countries to employ the “precautionary principle” to refuse goods that have used biotechnology anywhere in the production process.[50] (See Chapter 12.)

9.6 Risks and Opportunities for Market Development

Some proponents of biofuels envision a future international biofuel trade that will develop over time into a real “commodity market” that secures supply and demand in a sustainable way—sustainability being a key factor for long-term security. However, a number of policy and institutional barriers exist that can cause market distortions and harm market entry for biofuels. In addition to the tariffs, subsidies, and social and environmental obstacles already discussed, these potential barriers include increased control of the biofuels market by the oil industry (which could lead to price manipulation) and lack of infrastructure to provide for use of the biofuels in vehicles.

Factors leading to unreliable supply and demand also create market uncertainty and could impede biofuel development. Among the economic barriers these markets currently face are:

- Competition with fossil fuels on a direct production cost basis (excluding environmental and social externalities);
- Insufficient, unpredictable and/or inconsistent support policies promoting biofuels in many industrialized and some developing countries; and
- Relatively immature and unstable markets that are perceived as too risky for long-term or large-volume contracts.

The biofuel market also remains vulnerable to factors outside the control of trade boards and financiers. First-generation biofuels are vulnerable to crop failures and market prices for food. And because they comprise such a tiny share of the global energy trade, they will continue to be price takers in the short and medium-term (meaning that prices of biofuels will mirror spikes and dips in oil prices).

In response to these challenges, several mechanisms for reducing risks related to short-term imbalances in biofuel supply and demand are in the early stages of development. In May 2004, the New York Board of Trade took a step toward building institutional support for ethanol in the global market by negotiating an ethanol futures contract; as a result, ethanol is now traded under the symbol "XA."[51] This backing from the New York Board—a well-established global futures and options market for internationally traded agricultural commodities—may provide both producers and consumers with a greater level of assurance that their price and quantity needs will be satisfied, attracting more capital to the ethanol industry. However, some have expressed concern that a lack of transparency in commodity trading could hinder the biofuel market.[52]

Harmonized support policies (e.g., on the EU level) and new national incentives for biofuels offer opportunities for formalizing and stabilizing international biofuel trade by guaranteeing greater overall demand. The EU Strategy for Biofuels, released in February 2006, calls for greater guarantee of supply and demand for biofuels through a framework of incentives for publicly and privately owned vehicle fleets, including city and private bus fleets with dedicated fuel supplies (which can be easily adapted to higher blends of biofuels), farm and heavy goods vehicles (which would receive continued tax exemptions), and fishing fleets and vessels (which offer a potential market for biodiesel).[53] Towards a similar end, the Philippines and Thailand agreed in 2004 to strengthen bilateral and regional cooperation to promote biofuels by moving toward a regional standard for ethanol-blended gasoline, and by pushing ASEAN nations to encourage automobile manufacturers to make flexible fuel vehicles.[54]

9.7 Technical and Logistical Risks of Biofuel Trade

While countries continue to establish stronger relationships that bolster future trade in biofuels, existing infrastructure in major markets like the EU and the United States may continue to hamper these international fuel flows. For instance, concerns remain with regard to transit times and costs as well as the integration of biofuels into existing industrial and consumer transport uses. Below is a list of some of the major technical and logistical considerations for establishing an international biofuel trade.

- *In the longer-term, the limited ability to use different fuels may lead to a restricted availability of biomass fuels.* Vehicle and industrial installations must be compatible with biofuels. If technology is not available or installed to use biofuels, there may be a limited demand and thus less production.

- *Local transportation by truck may be very costly (both in biomass exporting and importing countries).* For example, in Brazil, new sugar cane plantations are being considered in the center-west, but the cost of transport and lack of infrastructure may be a serious constraint in the short term. Whether harbors and terminals have the capability to handle large biomass streams may hinder the import and export of biomass to certain regions. End-users located near harbors will be better able to avoid additional transport by trucks. If large-scale biofuels production is developed in new regions, it may take considerable time and capital to build more-efficient transport infrastructure.

- *Lack of significant volumes of biomass can decrease trade incentives.* In order to achieve low costs, large volumes need to be shipped on a more regular basis. Only if this can be assured will there be forthcoming investment on the supply side (e.g. the construction of pipelines to transport biofuels), and this will reduce costs significantly.

- *Disparities in production, export, and import conditions may slow the development of biofuels trade.* The most-efficient producers of biomass (e.g., certain developing countries) may not have the highly developed infrastructure necessary for trade, and may be geographically further from regions with highest demand. Investment in countries with low production costs to facilitate the export of first-generation biofuels may be unattractive to countries producing these fuels and transporting them using existing infrastructure.

In response to these problems, many governments are offering incentives to those entrepreneurs willing to develop next-generation biofuels. (See Chapters 4 and 17.) Foreign direct investment may also encourage the development of more stable infrastructure for biofuels transport. Already, China has invested more than €49.6 billion ($60 billion) in Brazil, Argentina, and Angola over the last five years to meet demand for agricultural products, €24.8 billion ($30 billion) of which was directed to Brazil largely for infrastructure improvements to facilitate agricultural exports.[55]

9.8 Consistent Fuel Standards for International Biofuel Trade

Fuel quality standards are an essential building block of successful international trade in biofuels for transport. Any fuel designed for use in modern vehicle engines, which have tight tolerances and advanced control systems, must meet stringent quality-control standards. Because biofuels are a relatively new fuel alternative, there is greater uncertainty regarding the performance of these fuels than for conventional gasoline or diesel fuels. Without fuel quality standards, there is a higher potential that bad batches of fuel will enter fuel distribution channels, and that resulting negative experiences might damage consumer confidence in biofuels—as occurred in Australia and set back the industry for a substantial period of time.

Biodiesel in particular can show significant differences in basic feedstock material. The saturated fat content of different vegetable oils varies considerably, which can affect key physical characteristics of the biodiesel produced, such as viscosity and “cloud point” (where wax crystals begin to form as fuel temperatures drop). The most commonly used oil for biodiesel in Europe, rapeseed, has a lower saturated fatty acid content, which makes it much less prone to fuel gelling problems in cold winter operating conditions. However, biodiesel fuels made from other vegetable oils that are more highly saturated can raise issues of clouding or gelling that must be addressed in order to avoid problems in vehicle start-up and operation. (See Chapter 15.)

For this reason and others, the European standard for biodiesel, though not raw-material specific, has technical parameters that limit the non-RME content to a maximum of around 25 percent. Expecting that EU demand for biofuels will exceed economical levels of production and encourage greater imports, the *EU Strategy for Biofuels*, released in February 2006, suggests amending the biodiesel quality standard EN 14214 to facilitate a wider range of vegetable oils, as long as there are no significant negative effects on fuel performance.[56] From

2007 onwards, German oil refineries will be required to blend 2 percent biofuel content in petrol until 2009, and 4.4 percent biodiesel content in conventional diesel.[57]

Already, other biofuel standards are in place, though they are not applied globally. The American Society for Testing and Materials (ASTM) initiated the development of biodiesel standards in 1994.[58] Recognizing the need for biodiesel quality control, many countries use the ASTM standards to assure the quality of biofuels.[59] (See Table 9–3.) For example, the United States has adopted ASTM standard D 6751 for pure biodiesel fuel used in blends of up to 20 percent with diesel fuel.[60] Biodiesel fuel that meets this standard and is legally registered with the U.S. Environmental Protection Agency is considered safe for sale in the United States. Similarly, Germany established a stringent biodiesel pre-standard specifically for fuel made from rapeseed oil (rapeseed methyl ester, or RME) in 1997. European standards for biofuels are set by the European Committee for Standardization (CEN) and implemented by national standardization bodies, e.g. the Deutsches Institut für Normung e.V. (DIN, the German Standards Institute). For B100, the quality control standard is DIN EN14214; the technical fuel specification for diesel, DIN EN 590, allows blends of up to 5 percent biodiesel fulfilling EN 14214. As standards are set by the market stakeholders, policy has only an indirect influence.

Table 9–3. Standards and Specifications for Biodiesel and Ethanol in Selected Regions or Countries

Country/Region	Fuel Type	Standards and Specifications (year adopted)
Australia	Biodiesel	Adapted from CEN (European Commission) and ASTM
Austria	Biodiesel	ONORM C1191 ON (1997)
Brazil	Biodiesel	ANP 255 (based on ASTM D6751 and CEN EN 14212)
Czech Republic	Biodiesel	CSN 656509 (5% RME); CSN 656508 (30% RME) (1998)
European Union	Biodiesel Ethanol	EN 14214 and DIN EN 590 (diesel standard allowing 5% biodiesel) DIN EN 228 (gasoline standard allowing 5% ethanol or 15 ethers)
France	Biodiesel	Gazette Officielle (1993)
Germany	Biodiesel	DIN E 51606 (1997)>replaced by EN 14214
Italy	Biodiesel	UNI 10946
Japan	Biodiesel	Not yet implemented, but under consideration
Philippines	Ethanol	Regional standard (2004)
South Africa	Biodiesel	Standard based on EN 14214
South Korea	Biodiesel	Modified ASTM 121-99 (plan to develop own standards by 2006)
Sweden	Biodiesel	SS 155436
Thailand	Ethanol	Regional standard (2004)
United States	Biodiesel	ASTM D 6751 (100%)

Source: See Endnote 59 for this chapter.

An example of a system of fuel quality standards that addresses biofuels directly is the BQ-9000 Quality Management Program, established in the United States in 2005 by the National Biodiesel Accreditation Commission. The intended benefit of this voluntary system is to provide biodiesel users, as well as engine and vehicle companies, with a feeling of confidence about the fuel. Key objectives of BQ-9000 are:

- To promote the commercial success and public acceptance of biodiesel;

- To help assure that biodiesel fuel is produced to and maintained at the industry standard, ASTM D 6751; and

- To avoid redundant testing throughout the production and distribution system.

This system accredits companies (both producers and marketers) rather than fuel, and helps to ensure that all biodiesel produced and sold in the United States will meet the same standard, D 6751. The program is a unique combination of the ASTM standard for biodiesel, ASTM D 6751, and a quality systems program that includes storage, sampling, testing, blending, shipping, distribution, and fuel management practices.[61] In Germany, the ACGM standard for biodiesel covers an even larger scale and is another instructive example of a biodiesel standard to be considered.

Quality-control standards have been adopted for ethanol as well. For example, in Europe ethanol blends of up to 5 percent in gasoline are subject to the technical fuel standard DIN EN 228. In 2004, the Philippines and Thailand established a regional standard for ethanol-blended gasoline in order to strengthen bilateral and regional cooperation in promoting consumer confidence and overall use of biofuels.[62] Several other countries have adopted standards for biofuels as well, while others are in the process of doing so.[63]

The International Energy Agency's Task 40 may contribute to biofuels standardization by collecting information on technical specifications required by consumers and conveying them to potential suppliers.

9.9 Conclusion

In the future, international trade policies and changes in the world market for agricultural goods are expected to positively affect growth in the international biofuel trade. As the demand for non-fossil liquid fuels grows, countries will increasingly adopt and refine standards for biofuel quality and support advancements in compatible transportation infrastructure. However, careful policy planning will be needed to ensure opportunities for sustainable trading relationships that support socio-economic development in the world's rural and agricultural regions.

In the near term, it is likely that a few large-scale producers, such as Brazil and Malaysia, will be the major exporters of biofuels. Importing nations may have the opportunity to set requirements for biofuel production and harvesting in these countries through bilateral agreements. Alternatively, these countries may prefer to keep and use their own biofuels to substitute for costly oil imports and conserve foreign exchange. Biofuel trade could also be hampered by countries that wish to protect domestic agricultural interests by imposing tariffs and other trade barriers that restrict foreign imports.

Trade policies can play an important role in advancing human and economic development in the world's rural areas. Preferential trade agreements and other policy instruments can be used to alleviate poverty in developing countries by helping these countries generate revenue through increased biofuel exports, or by allowing freer movement of technologies related to biofuels and other renewable energy technologies. Industrialized countries can also help poorer nations by transitioning distorting agricultural subsidies toward domestic energy crop production. These subsidies should be used to develop more-efficient next-generation feedstock that does not compete with traditional export commodities and hurt developing country producers.

Choices made in the trading arena will influence the overall sustainability of biofuel markets as well. There is a danger that large multinational cartels—whether oil companies or agribusiness companies—will simply replace unsustainable oil production with unsustainable biofuels production, maximizing profit but yielding undesirable social and environmental outcomes.[64] Ramping up biomass production for biofuel export could exacerbate many of the same problems caused by the export of traditional cash crops and energy resources, including ecological damage and fragmentation of agricultural communities.

One of the most touted energy security benefits of biofuels vis-à-vis oil is the creation of a more diversified and dispersed liquid fuel supply. While some suggest that ramping up large-scale production in tropical countries would achieve this end most efficiently, others suggest that biofuel production that meets local demand, rather than duplicating the centralized market control that oil companies display, is preferable. As production expands, the issue of whether biofuels should best be used locally or exported must be considered carefully, particularly in light of the various rural development and environmental implications. In general, trading relationships that benefit all contributors to the biofuels production chain—including small-scale farmers—will yield the greatest social, economic, and environmental benefits.

In the next 5–10 years, a technological transition is expected to take place that will replace first-generation biofuels with a second generation of fuels with substantially improved economic and environmental performance. The prices of these fuels relative to fossil fuels will be key in determining the rate of development of the world market for biofuels.

As biofuel production expands, additional trade-related questions will arise, including how to develop standards for fuel feedstock that are also food commodities, and whether biofuel standards should be voluntary or mandatory. These are also questions regarding how to develop these policies in accordance with WTO regulations, while also meeting demands for biofuel production that is both environmentally and socially sustainable. These issues are addressed in greater detail in Chapter 18.

PART IV. KEY ENVIRONMENTAL ISSUES

Chapter 10. Energy Balances of Current and Future Biofuels

10.1 Introduction

One of the primary incentives for expanding the production and use of biofuels worldwide is the potential environmental benefit that can be obtained from replacing petroleum fuels with fuels derived from more-renewable biomass resources. From an energy perspective, however, not all biomass is created equal, nor are all biofuel production processes equally efficient. When considering a biofuel promotion strategy, it is therefore useful to know which biofuels require more or less energy.

While biofuels themselves consist solely of energy photosynthesized with sunlight, producing them requires human effort and outside energy resources. Farmers capture the “free” energy of the sun by seeding, watering, and fertilizing plants. The biomass that grows must then be harvested, transported, and refined into a liquid fuel. All of these activities use energy, but people can choose more- and less-efficient biofuel production pathways. Some feedstock are more efficient and easier to process than others, and some farming and refining methods are more energetically frugal than others.

This chapter examines the relative energy requirements of both current and future biofuel production pathways. It discusses ways to measure the energy performance of biofuels and compares different fuel options based on these criteria. It also explores potential pathways for improving both the energy efficiency and fossil energy balance of biofuels, including options for achieving energy savings from these fuels in the near term.

10.2 Measuring Energy Performance

There are two primary measures for evaluating the energy performance of biofuel production pathways. These are:

- *Energy balance*—the ratio of energy contained in the final biofuel to the energy used by human efforts to produce it. Typically, only fossil fuel inputs are counted in this equation, while biomass inputs, including the biomass feedstock itself, are not counted. A more accurate term for this concept is *fossil energy balance*, and it is one measure of a biofuel’s ability to slow the pace of climate change.

- *Energy efficiency*—the ratio of energy in the biofuel to the amount of energy input, counting all fossil and biomass inputs as well as other renewable energy inputs. This ratio adds an indication of how much biomass energy is lost in the process of converting it to a liquid fuel, and helps to measure more- and less-efficient conversions of biomass to biofuel.

To illustrate the difference between these concepts, consider the example of wheat ethanol. The energy balance represents the number of joules contained in the ethanol divided by the number of joules used by people to plant, nurture, harvest, and refine the wheat grain. The energy efficiency, as defined here, represents the number of joules in the ethanol divided by the number of joules used by people to plant, nurture, harvest, and refine the wheat grain *as well as* the number of joules contained in the grain that is harvested. While the energy balance can exceed 1, the energy efficiency can *never* exceed 1, because some of the energy contained in the feedstock is lost during processing.

ENERGY BALANCE	**ENERGY EFFICIENCY**
<u>(Joules contained in the biofuel)</u> (Joules used by people to plant seeds, produce and deposit agricultural chemicals, harvest, transport, and refine the feedstock)	<u>(Joules contained in the biofuel)</u> (Joules used by people to plant seeds, produce and deposit agricultural chemicals, harvest, transport, and refine the feedstock, *plus the joules contained in the feedstock*)

Currently, tropical plants have more-favorable energy ratios because they grow in more ideal conditions for using sunlight and water and because they are often cultivated manually, with fewer fossil energy requirements and fewer inputs of fertilizer and pesticides. Temperate biofuel production pathways are usually less efficient, though they have become significantly more efficient in recent decades as agricultural practices have improved and fuel production mills have streamlined their operations. In the future, the energy cost of refining biofuels from lignocellulosic biomass will likely continue to exceed that of producing biofuels with conventional starch, sugar, and oil, but these lignocellulosic biofuels will bring with them greater quantities of residue bioenergy to use as processing energy.

10.2.1 Fossil Energy Balance

For biofuel promotion efforts aimed at reducing the use of fossil fuels, the fossil energy balance is a useful metric, although it is often called simply “energy balance” because fossil fuels are the predominate energy inputs in the United States and European Union (EU). Because they release sequestered greenhouse gases, sulfur, particulates, volatile hydrocarbons, and metals, fossil fuels generally do more harm to the environment than renewable fuels; thus, the more fossil fuel inputs a certain biofuel requires, the less energetically desirable it can be.

Table 10–1 compares the approximate fossil energy values for various biofuels.[1] Some production pathways are much more favorable than others, depending on the productivity of the crop, its responsiveness to fertilizer and irrigation inputs, the need for chemical pesticides, and the difficulty of harvesting and refining it into a fuel. Most importantly, a biofuel’s fossil energy balance depends on how much of these energy needs are provided by fossil fuel energy. Although both Brazilian sugar cane and cellulosic feedstocks such as switchgrass are productive plants, their especially favorable fossil energy balances are largely due to the fact that they are processed using the energy of biomass residues available at the mill.[2]

Ethanol feedstock such as sugar beets, wheat, and corn have been criticized because their fossil energy balance is close to 1, a threshold many consider the line between an energy sink and an energy source. But this view fails to account for two important nuances. First, ethanol is a liquid fuel that has qualities that make it useful in the existing transportation infrastructure. Since the natural gas and coal used to produce ethanol do not have this quality, it can be practical to lose energy in the process of converting these fuels into ethanol. Second, even crude petroleum must be refined into usable liquids. Diesel and gasoline have fossil energy balances between about 0.8 and 0.9, numbers that are more relevant for comparison than 1.

Table 10–1. Fossil Energy Balances of Selected Fuel Types

Fuel (feedstock)	Fossil Energy Balance (approx.)	Data and Source Information
Cellulosic ethanol	2–36	(2.62) Lorenz and Morris (5+) DOE (10.31) Wang (35.7) Elsayed et al.
Biodiesel (palm oil)	~9	(8.66) Azevedo (~9) Kaltner (9.66) Azevedo
Ethanol (sugar cane)	~8	(2.09) Gehua et al. (8.3) Macedo et al.
Biodiesel (waste vegetable oil)	5–6	(4.85–5.88) Elsayed et al.
Biodiesel (soybeans)	~3	(1.43–3.4); Azevedo et al. (3.2); Sheehan et al.
Biodiesel (rapeseed, EU)	~2.5	(1.2–1.9) Azevedo et al. (2.16–2.41) Elsayed et al. (2–3) Azevedo et al. (2.5–2.9) BABFO (1.82–3.71); depending on use of straw for energy and cake for fertilizer; Richards (2.7) NTB (2.99) ADEME/DIREM
Biodiesel (sunflower)	3	(3.16) ADEME/DIREM
Biodiesel (castor)	~2.5	(1.5); Kaltner (2.1–2.9) Azevedo
Ethanol (wheat)	~2	(1.2) Richards (2.05)ADEME/DIREM (2.02–2.31) Elsayad et al. (2.81–4.25) Gehua
Ethanol (sugar beets)	~2	(1.18) NTB (1.85–2.21) Elsayad et al. (2.05) ADEME/DIREM
Ethanol (corn)	~1.5	(1.34) Shapouri 1995 (1.38) Wang 2005 (1.38) Lorenz and Morris (1.3–1.8); Richards
Ethanol (sweet sorghum)	~1	(0.91–1.09) dos Santos
Diesel (crude oil)	0.8–0.9	(0.83) Sheehan et al. (0.83–0.85) Azevedo (0.88) ADEME/DIREM (0.92) ADEME/DIREM
Gasoline (crude oil)	0.80	(0.84) Elsayed et al. (0.8) Andress (0.81) Wang
Ultra low sulfur diesel	0.79	Elsayed et al.

Gasoline (tar sands)	~0.75	Larsen et al.

Note: These ratios do not count biomass inputs. Here, petroleum fuels cannot have a balance greater than 1 because crude oil is counted as an energy input, while biofuels processed entirely with non-fossil fuels could have a balance of infinity. The ratios for cellulosic biofuels are theoretical. Source: See Endnote 1 for this chapter.

10.2.2 Energy Efficiency

While the fossil energy balance accounts for just fossil energy inputs, measures of energy efficiency also include the biomass energy used to produce the fuel. Because this ratio includes the energy contained in the feedstock, energy efficiency must always be less than 1. Since petroleum feedstocks are counted in fossil energy balance as well, the energy efficiencies of producing gasoline and diesel are equivalent to their fossil energy balances.

While solid biomass energy may be more climatically benign than fossil fuels, it is not exactly "free." It can be used for other purposes, and it can also be used inefficiently. As discussed in Chapter 6, there are competing uses for biomass beyond the provision of transportation fuels, which could be more efficient. As cellulosic conversion processes develop, the efficiency of using them for liquid fuels should continue to be compared to the efficiency of using them for electricity, heat, or material production.

The energy efficiency of carbohydrate-to-ethanol pathways is relatively low, while that for oilseed-to-biodiesel pathways can be quite high. Converting plant oils into biodiesel is a simple process that yields an amount of fuel similar to the amount of plant oil put into the process. In contrast, fermenting sugars to ethanol alone entails a loss of about half the feedstock's mass and energy, which is released as carbon dioxide (CO_2) at the mill. Fuels derived from cellulosic fibers are even less energy efficient, because the fibers are more difficult to catalyze into sugars.[3]

These ratios would be different if the energy efficiency counted all the biomass contained in the crop as a biomass input. Here, sugar cane's efficiency ratio would diminish—thanks to the burning of cane leaves in the field—while the efficiency of fibrous biofuels would increase, since they would utilize a greater portion of the plants' total biomass.[4]

In general, petroleum fuels have a higher energy efficiency than biofuels. This is because petroleum has been collected and refined by geological forces over millions of years. Oil fields contain vast reservoirs of relatively pure hydrocarbons, and oil can be transported more efficiently than solid biomass feedstock (through pipelines more often than trucks); oil refineries are also many times larger than even big ethanol mills.[5] In contrast, obtaining fuels from biomass can require cultivating, collecting, and refining a more diffuse form of energy, preventing comparable economies of scale.[6]

In the future, the energy efficiency of biofuels is likely to compare increasingly favorably to that of petroleum fuels. While biofuel feedstock production and conversion processes are becoming more efficient over time, petroleum fuels are likely to become less efficient. Crude oil is becoming more difficult to extract, and stricter fuel emissions standards are requiring more intensive refining. The energy efficiency of even the world's largest oil fields has declined significantly as field operators now push the deepest oil out the wellhead by pumping vast quantities of steam or methane below. The energy cost of producing fuels from tar sands, a thick feedstock often hailed as the most promising source of “unconventional” oil left to be tapped, is much higher than conventional oils.[7] (See also Chapters 11 and 12.)

Meanwhile, biofuel production processes have become much more energy efficient in recent decades. Better plant breeds, more parsimonious farming methods, and larger processing facilities have all yielded increasing quantities of fuel since the 1970s. As the biofuel industry expands, fibrous residues such as sugar cane bagasse, dried distillers grains (DDG), wheat stalks, and lignin extracted during cellulosic conversion will likely become more important energy supplies. Though unlikely, it is possible that a biofuel’s fossil energy balance could approach infinity—if it is produced using entirely renewable energy.

10.3 Analysis of Energy Inputs

The energy inputs for biofuels fall into three main categories: the *agricultural energy* required to cultivate and/or harvest the feedstock; the *processing energy* required to convert the feedstock into fuels; and the *transportation energy* required to deliver feedstock to the refinery and deliver fuels to commercial depots.

Agricultural energy includes the natural gas used to manufacture fertilizers and pesticides, the fuels used to pump irrigation water to the fields, and the petroleum used to propel the plows, seeders/planters, and harvesters. In most cases, the production of nitrogen fertilizers requires predominantly agricultural energy: in the United States, for example, nitrogen fertilizers consume 70 percent of the energy farmers use to grow corn.[8] Processing energy includes the energy used in crushing and grinding the feedstock, producing reactive agents, and purifying the fuel.

Agricultural and processing energy are the two dominant energy uses in biofuel production, and their relative proportions vary depending on the type of fuel being produced. Producing ethanol from sugar beets or wheat typically requires around 20 percent agricultural energy and 80 percent processing energy. For biodiesel, the breakdown is 40 percent agricultural energy and 60 percent refining energy.[9] Transportation is also a small contributor to biofuels’ overall energy requirements.

In addition to these three areas of energy use, some analyses of energy balance also include the energy required to construct buildings and machinery, and in some cases the energy used in farmers’ manual labor. Adding these inputs increases the completeness of the energy picture, but rarely do these activities comprise more than a small share of total energy use.[10]

10.3.1 Agricultural Energy

The qualities and amounts of agricultural energy input vary significantly depending to the feedstock used. Wastes collected at forestry mills or agricultural processing centers (including sugar mills) may not technically require any additional energy input at all, since they are already part of existing processes.

Of dedicated plant feedstock, the agricultural energy requirements vary by species. Both corn and rapeseed can require large quantities of fertilizer, but soybeans, as nitrogen-fixing plants, need little to no nitrogen fertilizer. Corn grown in the western states of the U.S. corn belt (e.g. in Nebraska) uses a great deal of irrigated water, as does sugar cane grown in the northeastern region of Brazil.[11] But other corn belt states (e.g. Iowa) and the center-south of Brazil use rainwater, reducing their energy requirements. A plant such as jatropha can be very energy efficient, producing a high yield of oil in arid conditions with very little fertilizer.[12]

On the harvesting side, some biofuel feedstock is more difficult to harvest than others. Harvesting large monocultures of grain can be done with significant economies of scale, using industrial-size machines. By comparison, collecting oil seeds manually from trees is more arduous. However, combine harvesters utilize fossil fuels, while human and animal laborers often expend a form of renewable energy.[13]

10.3.2 Processing Energy

The inputs for processing energy vary by biofuel production pathway. Transesterifying plant oils into biodiesel is much easier than hydrolyzing starches and fermenting sugars into ethanol. This is because the ethanol process entails the breakdown of molecules as well as the distillation of ethanol from water. (Starches must be hydrolyzed into sugars, the sugars fermented into ethanol, then the ethanol distilled from water several times.) In contrast, vegetable oils can be mixed with methanol and a catalyst to produce biodiesel. This is a simpler process, and it is worth noting that most of the energy required is used to refine methanol from natural gas. In Europe, rapeseed methyl ester (RME) biodiesel uses only half as much overall energy, and one-third as much processing energy, as wheat ethanol.[14]

10.3.3 Transportation Energy

Transportation energy makes up only a small proportion of the energy used to produce biofuels. One reason for this is that biofuels are not transported very far—processing facilities are usually located within 200 kilometers of feedstock fields, and so far the fuels are consumed largely within the producing country. However, the relative share of transportation energy could increase as international trade in biofuels expands. (See Chapter 9.)

Energy tabulations have found that transportation accounts for 2–5 percent of biofuels' energy inputs.[15] In contrast, as much as 10 percent of the inputs for petroleum fuels can go to transportation. This is because crude oil is a more concentrated resource and is often refined and used far from the wellhead. By transporting crude oil over longer distances, oil companies can benefit from greater economies of scale at the refining stage; however, as oil reserves become more concentrated in regions like the Middle East, the transportation costs for petroleum fuels will likely increase further.[16]

10.3.4 Fossil vs. Biomass Energy

In the United States and Europe, most of the energy used to process biofuels comes from fossil fuels. Natural gas provides the bulk of the energy for producing fertilizers and pesticides, and diesel fuel powers most of the tractors and trucks involved in production and transport. In general, larger wet milling facilities are powered largely by coal, while dry mills are powered largely by natural gas.[17]

In contrast, virtually all the processing energy used in Brazil comes from renewable sources. Bagasse, the fibrous residue that remains after sucrose is extracted from sugar cane stalks, contains a vast amount of energy. It can provide all the energy used to process ethanol, and, in more efficient operations, a substantial quantity is left for other purposes, such as electricity generation for export to the grid. Wastes from Brazil's distilleries are also used to fertilize a portion of the sugar cane fields, reducing the energy needed to manufacture fertilizers. The result is that Brazilian sugar cane ethanol has a much better fossil energy balance than other biofuel production pathways.

10.3.5 Co-products

An accurate accounting of a biofuel's energy balance also considers the energy required to manufacture the co-products that are often produced alongside these fuels. In a typical dry mill for ethanol production in the United States, about one-third of the energy used to process corn kernels goes to the production of dried distillers grains, an animal feed.[18] Similarly, biodiesel facilities extract large quantities of glycerin from the plant oils (for use in soap, etc.), offsetting the energy use of the biodiesel fuel by about 20 percent.[19] These offsets are now included in most calculations of the fossil energy balance of biofuels, with some studies also accounting for the energy gains obtained from *not* producing an animal feed or chemical feedstock via another pathway.

10.4 Improvements in Efficiency and Fossil Energy Balance

The energy efficiency of biofuel production has been improving for several decades and is likely to continue to improve as producers seek to reduce their energy costs. Simultaneously, the use of fossil fuel energy can be replaced by energy from biomass co-mingled in biofuel production systems (as with bagasse in Brazil). Both of these lead to improvements in the energy balance of biofuels.

The farming of biofuel feedstock has become more efficient as farmers have improved crop yields while minimizing energy inputs. In the United States, corn yields have increased at an average annual rate of 1.2 percent over the last 40 years, and increased eight-fold over the last 100 years. The amount of corn grown per kilogram of nitrogen fertilizer has increased by 70 percent in the last 35 years, and the fertilizer itself has become more efficient as well. Today, a kilogram of nitrogen fertilizer can be produced for half the energy required in the 1970s.[20]

Converting crops into fuels has likewise become more efficient. Ethanol yields per kilogram have increased by 22 percent in the United States since the 1970s (for corn) and by about 20 percent in Brazil (for sugar cane).[21] This is because of better crushing methods and, in the United States, the use of enzymes that hydrolyze starches into sugars more effectively.[22] Larger production plants also bring greater economies of scale: they can house their own cogeneration plants to produce both electricity and steam, which not only use fossil fuels more efficiently, but also provide the option of co-firing with biomass residues.[23]

These improvements appear likely to continue. Agronomists expect crop yields to continue increasing, while better soil management practices, such as no-till farming, can save energy by reducing the need to plow.[24] In the future, to reduce the use of fossil fuels, biomass could replace natural gas as a feedstock for nitrogen fertilizers.[25]

Biorefining will also continue to become more efficient. In the United States, advanced enzymes are able to convert starch into sugars at much lower temperatures than before, while newer strains of yeasts are able to tolerate higher concentrations of ethanol, reducing the energetic requirements for distilling the ethanol from water. In Brazil, fuel production procedures have been intentionally inefficient, since they were a way to burn off huge piles of "waste" bagasse. But as the value of bagasse as an energy source is better appreciated, it is being used more frugally.[26] Likewise, utilizing other co-products will bring further improvements in energy use.

For example, cattle raised near ethanol plants can eat “wet distillers grains,” skipping the energy-intensive process of dehydrating these into a more transportable dry form.[27]

As new fuel conversion technologies develop, refiners will be able to exploit large amounts of “raw” biomass. Several mill owners in the U.S. state of Iowa already have plans to burn dried distillers grains, wood wastes such as sawdust, and corn stover and wheat stalks (normally left to deteriorate on fields) for processing power.[28] In Brazil, sugar cane growers could salvage cane leaves and tips, which contain as much energy as bagasse but are traditionally burned off before harvest. In processes that use new enzymes to hydrolyze fibers into sugars, the impregnable lignin residue (about one-third of the plant’s biomass) would be most effective as a source of processing heat.[29] In new gasification processes, refiners could easily burn a portion of the biomass feedstock for process energy.[30] (See Chapter 5 for more detail on these technologies.)

Agricultural and forestry residues, as well as other “wastes,” would require no additional cultivation energy. In some cases, as with bagasse or pulp mill wastes, the feedstock has already been collected by procedures intended to yield other products. In other cases, farmers could collect residues at the same time they harvest crops, using new “single-pass” harvesters being developed for this purpose. The efficiency advantage of wastes will be reflected in more favorable energy balances.[31]

Energy crops, for their part, require less maintenance. Because they are usually perennial crops, they do not need to be replanted, and they require less pesticide and fertilizer. Cultivating them thus entails fewer tractor trips. Agronomists also expect they can increase yields of these crops significantly—by perhaps more than double—since breeders will be able to focus on simpler characteristics (quick growth of the entire plant) and since plants such as switchgrass and miscanthus have not yet benefited from intensive breeding.[32]

10.5 Conclusion

Clearly, some biofuel production pathways are more efficient than others, with geography being the principle determinant of efficiency. Since transportation energy accounts for only a small share of a biofuel’s overall energy use, this suggests that it would be more energetically efficient for countries with temperate climates to import biofuels (e.g. made from sugar cane or palm oil) than to produce them at home. It would be more efficient to transport the final fuels, rather than just the feedstock, because the fuels are more energetically dense.

It is generally acknowledged that biofuels produced from temperate oil seeds, sugar beets, wheat, and corn have limited ability to displace other fuels, because of either their low yields or high input requirements. However, this feedstock is still more energetically efficient than cellulosic biofuels, when considering all of the energy inputs including the biomass used to provide the energy needed for the conversion process. While cellulosic conversion technologies will improve over time, in the near term, cellulosic biomass has the greatest potential as a fuel to provide process energy for conventional (first-generation) biofuels, providing a means to significantly improve the overall fossil energy balance of these fuels. As cellulosic conversion becomes more viable, analysts should continue to evaluate the most efficient uses of cellulosic biomass, raising the importance of “energy efficiency” metrics.

When considering strategies for slowing the pace of climate change, the fossil energy balance of different biofuel production pathways can be a useful measure of their relative effectiveness.

It is worth emphasizing that the fossil energy balance of biofuels could theoretically approach infinity, but only if renewable energy alone is used to cultivate, harvest, refine, and deliver biofuels. However, fossil energy balance does not take into account other ways that biofuel production contributes to climate change, such as changes in land use.

Chapter 11. Effects on Greenhouse Gas Emissions and Climate Stability

11.1 Introduction

One of the major drivers of biofuel developments worldwide is concern about global climate change, caused primarily by the burning of fossil fuels. There is substantial scientific evidence not only that the Earth is warming, but that this warming is happening at an accelerating rate, as emissions of greenhouse gases (GHGs) continue to rise.[1]

Transportation, including emissions from the production of transport fuels, is responsible for about one-quarter of global energy-related GHG emissions, and that share is rising.[2] Transport accounts for 27 percent of total emissions in the United States (including 42 percent of carbon dioxide emissions) and 28 percent of total emissions in the European Union (EU).[3] According to the United Nations, the EU's GHG emissions declined overall between 1990 and 2003, but the share of emissions from the transport sector increased by 24 percent.[4] It is estimated that transport-related GHG emissions in the EU-15 will increase 34 percent above 1990 levels by 2010 if no further measures are taken to slow their growth.[5]

In rapidly industrializing developing nations like China and India, which now lead global growth of vehicle sales, emissions from the transport sector will likely rise far faster over the coming years. For the near term at least, unless human behavior patterns change significantly, biofuels and improvements in energy efficiency offer the only options for dramatically reducing demand for oil and transport-related GHG emissions.

This chapter discusses the current and potential impacts of biofuels on the global climate, both through the different stages of biofuels production and use and over the entire life cycle. It provides estimates of potential GHG emissions reductions associated with biofuels for transport relative to emissions from petroleum fuels.

11.2 Biofuels and the Global Climate

In the case of petroleum products, such as gasoline and diesel, a life-cycle analysis of the climate impact includes all GHG emissions associated with the following life-cycle stages: the exploration and production of oil; the transport and refining of oil for use; the storage, distribution, and retail of oil; the fueling of a vehicle; and the evaporative and tailpipe emissions associated with using the oil in a vehicle. For biofuels, the stages to be considered include: the planting and harvesting of crops (including impacts on soil carbon storage, emissions associated with energy required for irrigation, and the production and use of fertilizers and pesticides); processing the feedstock into biofuel (including co-products); transporting feedstock and the final fuel; storing, distributing and retailing biofuel; and, finally, the impacts of fueling a vehicle and the evaporative and tailpipe emissions resulting from combustion.[6,7]

The climate impact of biofuels depends greatly on their fossil energy balance—that is, how much energy is contained in the biofuels themselves versus how much fossil fuel energy was required to produce them.[8] (See Chapter 10.) This, in turn, depends on the energy intensity of feedstock production (including the type of farming system and inputs used), processing, and transporting the feedstock and final product.

Unlike fossil fuels, which contain carbon stored for millennia beneath the Earth's surface, biofuels have the potential to be "carbon neutral" over their life cycles, emitting only as much as the feedstock absorbs. This is because biofuels are produced from biomass, and exactly the same amount of carbon dioxide (CO_2) that is absorbed from the atmosphere by the plants through photosynthesis is set free through combustion.[9] This accounts for an almost closed CO_2 cycle. (See Appendix A–7 for a flow chart of bioenergy vs. fossil energy.[10])

Outside of combustion, the primary sources of GHGs during the life cycle of biofuels occur during production of these fuels. CO_2 and other greenhouse gases are emitted from the cultivation of crops, the manufacture of nitrogen fertilizers, and the consumption of fossil fuels in the machines used for growing feedstock and refining it into biofuel. On the other hand, biofuel production results in the generation of co-products, which can substitute for products manufactured conventionally and the non-renewable primary energy used in their production.[11]

With the exception of a few studies that report associated increases in GHG emissions, most studies find a significant net reduction in global warming emissions from both ethanol and biodiesel relative to conventional transport fuels.[12] There exists broad agreement that the use of biofuels, made with today's technologies, can result in significant net reductions in carbon emissions, and that reductions with next-generation feedstock and technologies will be even larger.

However, figures vary widely due to differing assumptions about factors such as management practices, conversion, and valuation of co-products. Estimates differ depending on assumptions about: feedstock used; land use changes (where and how much additional land will be required, and what the bioenergy crops are replacing); crop management (including use of fertilizer, tilling of soil); crop yields; processes and their efficiencies (including fossil inputs for refining); the relative efficiencies of gasoline and ethanol (diesel and biodiesel, including blends, have about the same vehicle efficiency); credits attributed to co-products; and the methodologies used to calculate total life-cycle emissions.[13]

Estimates also vary depending on the GHGs that are considered and their relative impacts. Most studies consider emissions of CO_2, nitrous oxide (N_2O), and methane, but many omit ozone. Ozone affects climate directly but it is not emitted during the fuel cycle; instead, it is formed by photochemical reactions with other gases that are emitted, including nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane organic compounds. In addition, most studies do not look at other gases that might also be GHGs—including hydrogen (via its effect on ozone) and particulate matter—which could alter the calculated life-cycle GHG balance of these fuels.[14] It is important to keep in mind that the reference system (petroleum-based fuels) is rarely ever evaluated with full GHG accounting, such as methane emissions associated with production.[15]

The equation could be even more favorable for biofuels if waste streams and/or agricultural and forestry residues are used as feedstock. (See Chapter 4.) However, while the conversion technologies necessary to convert cellulosic residues and other wastes to biofuels currently exist, they have not yet been commercialized.* Most estimates for these technologies come

* On the other hand, anaerobic digesters for converting animal and human waste to biogas are fully commercialized and the benefits are well known. There are also serious demonstration and commercialization projects focused on hydrolysis for ethanol; demonstration and co-production (with

from engineering studies; but it is assumed that net GHG emissions will be dramatically lower with these technologies.

11.2.1 Feedstock Production and Harvest

The production of feedstock, particularly the change in land use and the use of fertilizer, is generally the most GHG-intensive stage in the life cycle of biofuels. Gases released as a result of feedstock production include CO_2, N_2O (from nitrogen fertilizer application and decomposition of leaf litter), and methane.[16]

Different crops have different GHG emission or carbon sequestration characteristics (the ability to capture and store carbon), depending on factors such as fertilizer requirements and root systems. Associated emissions also vary depending on where the feedstock is grown because climate, solar resources, and soil productivity all affect crop yields and application rates of fertilizer.

The following section discusses the climate related impacts of biofuels feedstock production and harvest, looking more closely at the affects of land-use change, crop management and crop selection, and harvesting.

Land-Use Change

On a global basis, organic matter in soils contains more than twice the carbon in atmospheric CO_2, and additional carbon is stored in biomass. Because these pools of carbon are so large, even relatively small increases or decreases in their size can be of global significance.[17] The amount of carbon stored (or sequestered) in plants, debris, and soils changes as land use is altered, including when biomass is grown and harvested. Because increases in land area used to produce feedstock can result in large releases of carbon from soil and existing biomass, they can negate any benefits of biofuels for decades.[18] And because changes could extend over long periods of time and then reach a new equilibrium, it is important that any analysis be time-dependent.[19]

To highlight the importance of dramatic one-time changes in land-use, it is relevant to note that the burning associated with forest clearing in Indonesia and Malaysia was one of the largest contributors to global GHG emissions in 1997.[20] As discussed in Chapter 12, much of this clearing is to open the land for new palm oil plantations. In addition to the potential impacts for the climate on a global scale, devastation of vast forestlands could cause significant climatic change on a regional basis. Studies reveal that wide-scale destruction of forests can affect the hydrologic cycle and regional climate, reducing precipitation and increasing temperatures.[21] For example, destruction of the Amazon could lead to serious disruptions in hydrological cycles, threatening to reduce rainfall in inland areas like Brazil's *cerrado*, a vast expanse across the high plains that is home to some 935 species of birds and nearly 300 mammal species, including many that are threatened or endangered.[22]

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coal/natural gas) facilities for gasification (Fischer-Tropsch fuels and dimethyl ether); and Shell and Chevron recently announced that they will soon begin F–T production from co-gasification from coal and biomass in Europe. Per André Faaij, Coordinator, Research Energy Supply & System Studies, Copernicus Institute, Utrecht University, The Netherlands, e-mail to Suzanne Hunt, Worldwatch Institute, 10 March 2006.

In general, converting land from natural cover to intensive agriculture with annual crops reduces plant biomass above ground and, over time, emits carbon from the soil (the reverse of a GHG benefit) as inputs of debris decline and as increased soil temperature and aeration result in further losses. Even converting to “sustainable” energy crops can reduce soil carbon content, for instance if wild forests are leveled to produce biofuel feedstock.[23]

If, on the other hand, land is converted from existing annual crops to perennial herbaceous species, such as native grasses, organic matter in the soil progressively increases; with woody crops, organic matter increases yearly over the term of the rotation.[24] This is because perennial crops tend to deposit more carbon in the soil as roots, and the absence of tillage slows decomposition of soil matter. Thus, it is likely that the cultivation of perennial biomass crops in areas previously used for annual crops will increase the organic carbon content of soil.[25]

In fact, soils have far greater capacity to store carbon than the temporary CO_2 bond of biomass crops. But any changes will take time.[26] In addition, the potential to sequester additional carbon is very site specific and depends on former and current land uses, agricultural practices, climate, and soil characteristics.[27] And the storage reservoir in soil exists only when potential reservoirs are not filled; in other words, “all else being equal, there is a maximum amount of carbon that can be stored in vegetation and soils in any climate.”[28] Further, carbon sequestration is reversible. Any carbon that does accumulate in soil or biomass could be released if the use or management of land is later converted back to previous uses, such as annual crops.[29] Thus, carbon storage in soils can be only a short-term option for reducing GHG emissions.[30]

Crop Management

Crop management—including the level of fertilizer and pesticide use, the fuels used to drive farm machinery, means of irrigation, and treatment of the soil—also plays an important role in determining the climate impact of biofuels. The burning of diesel fuels to drive tractors and other farm machinery releases CO_2, in addition to NO_x and hydrocarbons, which help to create ozone. And irrigating crops using fossil energy also releases CO_2. The western corn/soybean belt of the United States, in particular, requires high levels of irrigation, as do large areas of rapeseed cultivation in Europe and the smaller sugar production areas in northeastern Brazil. Seed cultivation, meanwhile, requires a share of all the energy inputs during a previous crop cycle.

The most significant factor in terms of climate impact, however, is chemical fertilizers, which require large amounts of fossil energy input. Typically, fertilizers and pesticides are manufactured using natural gas as an input, and nitrogen (N) fertilizer in particular can require vast amounts of natural gas to produce. Pesticides generally are fossil fuel-based as well, increasing energy inputs and therefore associated GHG emissions. (See Chapter 12 for more on the environmental impacts of chemical fertilizers and pesticides.)

Some of the nitrogen fertilizer used on fields is eventually emitted as nitrous oxide (N_2O), which is released directly from the soil or through runoff water. N_2O is a potent greenhouse gas that accounts for 6 percent of anthropogenic GHG emissions, and inorganic N fertilizer accounts for about 60 percent of this total; leguminous crops like soybeans account for another 25 percent. Atmospheric concentrations of N_2O are increasing at a rate of 0.2–0.3 percent annually.[31] Emissions rates depend on soil type, climate, crop, tillage method, and application rates.

Primary energy demand for producing N fertilizers varies from place to place, as does fertilizer use. Use also differs by crop type.[32] For example, large amounts of fertilizer are used for corn farming, and at high enough quantities that fertilizer production and distribution alone can account for 70 percent of all agricultural energy inputs, and an even greater proportion of the GHG emissions due to its degradation into N_2O.[33] In contrast, soybeans, which are leguminous nitrogen fixers, require substantially less N fertilizer. Research is needed to determine whether intercropping of legumes, such as soybeans, with perennial biomass crops can reduce the need for N fertilizer.[34]

Any efforts to reduce the use of fertilizers and pesticides, or to replace fossil fuel use in powering farm equipment and tilling the soil, could significantly lower associated emissions. For example, biofuels and renewable power can be used to fuel and power equipment instead, reducing the climate impact. Rather than tilling the soil, farmers could plant perennial crops and/or adopt conservation tillage practices involving direct seeding, which actually increases soil carbon storage by leaving organic matter relatively undisturbed. [35]

Feedstock Selection

The feedstock selected for ethanol and biodiesel production is critical. It determines everything from the energy yield per unit of land, to the use of fertilizer, to the amount of carbon that can be sequestered in the soil.

For ethanol, grains such as corn, barley, and wheat generally produce high concentrations of starch, but they are less efficient in their use of land and fertilizer than is sugar cane.[36][*] European wheat, for example, yields about 2,500 liters of ethanol per hectare; European rapeseed, used to make biodiesel, yields about 1,200 liters of fuel per hectare.[37][†]

In contrast, palm oil trees can produce five times as much oil per hectare as rapeseed, and more than 13 times as much as soybeans. While less productive than palm trees, jatropha bushes are still significantly more productive per hectare than rapeseed.[38] And test plots of switchgrass in the United States have yielded enough for about 10,900 liters of ethanol per hectare each year.[39] Miscanthus and hybrid poplars also have the potential for high yields.[40]

In addition to their high yield potential per unit of land, such energy crops require less fertilizer and pesticide input, do not require tilling, and can sequester significant amounts of carbon in the soil. [41] Because perennial crops also have the capacity to restore soil carbon contents over time, they could help to improve the quality of degraded lands. Switchgrass, for example, actually expands its deep root system when harvested, thereby increasing organic matter in soils and increasing carbon sequestration.[42]

But the life-cycle GHG impact of energy crops ultimately depends on what these crops are replacing. If they replace natural grasslands or forests, GHG emissions will likely increase; if, on the other hand, energy crops are planted on unproductive or arid land where conventional crops cannot grow, or in place of annual crops (for example, in place of corn grown for ethanol, or rapeseed for biodiesel), they have the potential to significantly reduce associated emissions. In

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[*] Further, processing them into ethanol requires an additional step that is not needed for making ethanol from sugar cane and sugar beets: hydrolyzing the starch into sugars at high temperatures before fermentation. This increases energy requirements.
[†] Note that biodiesel has more energy content per liter than does ethanol.

addition, many plants, such as jatropha and pongamia, can thrive on unproductive or arid lands where conventional crops cannot grow.

Finally, crop and forest residues, animal wastes, and the organic part of municipal waste could all be used to produce fuel with next-generation technologies. (See Chapters 4 and 5.) These are feedstock that might otherwise have no other uses, do not in themselves require land, chemical inputs, or irrigation, and that can provide useful energy.

Harvesting

The way crops are harvested, including the procedure, timing, and machinery used, all affect the level of GHG emissions associated with the process.

For example, on some soils the removal of crop residue can result in the release of soil carbon (the opposite of sequestration), in addition to having detrimental impacts on other factors that are important for healthy soil function. There is evidence that residue removal changes the rate of physical, chemical, and biological processes in the soil, by causing more fluctuations in soil temperatures and increased water evaporation. One study estimates that residue harvesting can reduce corn-derived soil organic carbon by 35 percent relative to when it is retained; this is averaged over all tillage systems.[43] Other studies have found that soil organic carbon with corn crops is greatest under no-till systems in which residues are allowed to remain on the ground, while it is lowest in no-till when stover is removed.[44]

While surface matter is important, roots are the largest contributor to soil organic matter, and thus the most significant part of the plant for carbon accrual.[45] In fact, one of the benefits of the perennial plant switchgrass is that its root system actually grows and sequesters more carbon in the soil after the crop is harvested each year, as noted above.[46]

The timing of harvest can also be important—for example, trees should be harvested in winter so that leaves are not removed from the area. In addition, tillage may play an even greater role than residue removal in the release of carbon from soils.[47] Leaving some residue on the ground, and planting cover crops which prevent soil loss after harvest, can help to limit this problem.

The use of machinery, which generally runs on diesel, also results in emissions of GHGs. Pre-harvest burning of sugar cane, a common practice in Brazil, releases as much as one third of the crop's biomass into the air as CO_2, with some amount of methane and NOx emitted also.[48] This represents a lost opportunity, because the dry matter could be used as process energy to offset the use of fossil fuels.

11.2.2 Refining Feedstock into Biofuels

In refining, the most significant factors with regard to climate impact are the conversion efficiency of the refining process or facility, energy inputs and outputs, source of process energy (for example, fossil versus renewable power), and the emissions attributed to co-products. The efficiency of conversion from feedstock to biofuel is important because it drives the amount of feedstock required for a given volume of biofuel, which in turn affects the amount of land and fossil fuel input needed to grow, transport, and process the crops.[49]

Significant amounts of energy—in the forms of process heat, mechanical energy, and electricity—are needed for the refining process. In North America and many other regions, most of this energy is derived from natural gas and coal, used both directly and for electricity generation.[50] However, residual biomass could be burned instead to generate electricity or steam, reducing or even eliminating the need for external energy inputs. In Brazil, bagasse (a byproduct of sugar cane crushing) is used for energy production, enabling mills and distilleries to be almost entirely energy self-sufficient; some even sell their surplus electricity to the power grid.[51] Sugar factories in the U.S. state of Hawaii also burn bagasse to provide steam and electricity for sugar processing, and sell their excess power to local utility companies.[52] Transitioning to renewable energy for the refining process in this way could significantly reduce life-cycle GHG emissions associated with biofuels production, particularly if it replaces coal.[53]

When biofuel plants produce co-products as well—such as animal feed (from ethanol production) or glycerin and fatty acids for soaps (from biodiesel production)—the GHG emissions released during the refining process are "shared," meaning that the amount attributable to biofuels is lower than would otherwise be the case. Co-products can replace competing products that require energy to produce; thus, they can offset energy needed to make those products another way. For example, animal feed made while refining corn into ethanol or soybeans into biodiesel can reduce the need to grow corn or soy specifically for animal feed production. The energy saved can partly offset the energy needed to produce biofuels.[54] Co-products, such as straw, could also be converted into more fuel. Current processes make little use of this resource, but the potential for saving conventional energy is significant.[55]

Sensitivity analyses reveal that net energy calculations (and thus associated GHGs) are most sensitive to assumptions about the allocation of co-products.[56] Thus, whether or not they are included, and how, can make a significant difference in estimations of the emissions associated with biofuels production. According to Fulton et al. (2004), most studies that look at the life-cycle GHG emissions of ethanol from corn, for example, assume that various co-products reduce the net emissions of ethanol by 5–15 percentage points.[57] Armstrong et al. (2002) mention co-product credits for rapeseed methyl ether (RME), including animal feed and glycerin, ranging from 5–14 percentage points.[58]

11.2.3 Transport of Feedstock and Fuel

Biomass feedstock is generally transported from fields to biorefineries by truck, traveling a few dozen to a few hundred kilometers.[59] Each truckload is much smaller than an oil tanker's load and thus does not benefit from the same economies of scale. And trucks must carry a great deal of excess water, fiber, and protein contained in the plant feedstock, which increases transport energy requirements. Transport by train or pipeline, where feasible, could significantly reduce associated emissions. But today the fuel requirements—and thus associated emissions—are minimal for distribution of biofuels to the fueling station.[60] A study by the U.S. National Renewable Energy Laboratory (NREL) comparing soybean diesel to petroleum diesel concluded that transporting crude oil consumes about five times more energy (per unit of final fuel) due to longer transport distances, meaning that resulting GHG emissions for transportation are far lower for soybean diesel than conventional diesel.[61]

While there is relatively little trade of biofuels on a global scale today, this situation is changing very rapidly. Trade will increase significantly as consumption rises and as domestic demand for biofuels in some countries exceeds their potential to produce them (something already occurring in Europe). (See Chapter 9.) Then, long-distance transport will become a more considerable factor for biofuels. At the same time, the distances that feedstock and, particularly fuels, are transported have only a small impact on life-cycle CO_2-equivalent emissions because the net energy requirements of long-distance transport (generally via ship) are relatively small per volume of fuel shipped.[62] Hamelinck, Suurs and Faaij (2005) conclude that shipping of refined solid biomass and biofuels is possible at relatively low costs and modest energy losses.[63] Most important will be minimizing the transport of wet, untreated biomass.[64]

11.2.4 Combustion

The combustion of biofuels results in the release of carbon dioxide into the atmosphere, but because the emissions are already part of the fixed carbon cycle—absorbed by plants as they were growing—they do not contribute to new emissions of CO_2. NREL estimates that biodiesel from soybeans emits almost 10 percent more CO_2 than does petroleum diesel—due to more complete combustion and "the concomitant reductions in other carbon-containing tailpipe emissions"; however, most of this is renewable, or recycled in growing soybean plants.[65]

11.3 Life-Cycle Impacts of Current-Generation Biofuels

Ultimately, it is the net emissions over the full life cycle of biofuels—from changes in land use to combustion of fuels—that determine their impact on the climate. Research on net emissions is far from conclusive, and estimates vary widely. Calculations of net GHG emissions are highly sensitive to assumptions about system boundaries and key parameter values—for example, land use changes and their impacts, which inputs are included, such as energy embedded in agricultural machinery, or the energy needs of farm laborers (generally not included); and how various factors are weighted.

According to Quirin et al. (2004), who reviewed more than 800 studies and analyzed 69 of them in detail, the primary reasons for differing results are different assumptions made about cultivation, and conversion or valuation of co-products.[66] Larson (2005), who also reviewed multiple studies, found that the greatest variations in results arose from the allocation method chosen for co-products, and assumptions about N_2O emissions and soil carbon dynamics.[67] In addition, GHG savings will vary from place to place—according to existing incentives for GHG reductions, for example.[68] And the advantages of a few biofuels (e.g., sugar cane ethanol in Brazil) are location specific.[69] As a result, it is difficult to compare across studies; however, despite these challenges, some of the more important studies point to several useful conclusions.

The majority of life cycle analyses carried out thus far look at grains and oilseed crops in North America and the European Union; the exceptions are a study on sugar cane ethanol in Brazil; one on sugarcane ethanol in India; and one on biodiesel from coconut.[70] Further, most studies have looked at ethanol, biodiesel, and ETBE.[71] A limited number have considered vegetable oil and biogas, DME, and biomass-to-liquid (BTL) fuels. But there have been no studies to date on biodiesel from palm oil, cassava, or oilseed plants like jatropha and pongamia, or on pyrolysis oil diesel or HTU (Hydro Thermal Upgrading) diesel.[72] In addition, no locally relevant lignocellulosic energy crop studies have been done in the developing country context.[73]

It should be noted that a few studies stand out from the rest in that they have reported *increased* emissions from biofuels relative to conventional petroleum fuels. For example, Pimentel (1991, 2001) has estimated that ethanol derived from corn results in a 30 percent increase in life-cycle GHG emissions over gasoline.[74] Other studies reporting an increase are by Pimentel and Patzek.[75] They stand apart from the rest because they incorrectly assume that ethanol co-products should not be credited with any of the energy input (and thus associated emissions) in feedstock growing and fuel processing. They also include data that are outdated and do not represent the current agricultural and refining processes, and/or are poorly documented and thus cannot be fully evaluated.[76]

The other notable exception is a series of studies by Delucchi, who also finds that biofuels from many of the current feedstock have higher life cycle emissions than petroleum fuels.[77] Delucchi (2005) includes co-products in his analysis and assumes that production processes will continue to become more efficient and will switch to low-emitting process fuels (such as renewable power), and he is continuously updating his model and data.[78] His work differs from other studies primarily in that he includes a detailed accounting of the entire nitrogen cycle, uses comprehensive CO_2-equivalency factors (accounting for many GHGs that most other studies do not incorporate), and has a comprehensive and detailed accounting of land-use changes and resulting impacts on the climate.[79]

This analysis notwithstanding, the vast majority of studies have found that, even when all fossil fuel inputs throughout the life cycle are accounted for, producing and using biofuels made from current feedstock result in substantial reductions in GHG emissions relative to petroleum fuels.[80] The following subsections consider ethanol and biodiesel separately.

11.3.1 Ethanol

As mentioned earlier, there are significant variations in findings for life-cycle GHG reductions associated with ethanol.[81] (See Table 11–1.) However, most studies show that as ethanol blend levels rise, any emissions benefits associated with ethanol increase as well. According to Wang et al. (1999), this occurs because more ethanol (and thus less petroleum fuel) is used and because vehicle fuel economy improves as the share of ethanol increases.[82]

Farrell et al. (2006) looked at six representative studies of fuel ethanol from corn, adjusting them for commensurate system boundaries. They found that, depending on the study input parameters (such as energy embodied in farming equipment), switching from gasoline to corn ethanol yielded anywhere from a 20 percent increase in emissions to a 32 percent decrease. Their best estimate, with today's yields and technology, is that life-cycle emissions decline by 13 percent.[83]

Larson, who reviewed more than 30 life-cycle assessment studies for various biofuels, found that ethanol from wheat ranged from a 38 percent benefit to a 10 percent penalty.[84] Delucchi estimates that emissions from corn ethanol can range from a 30 percent reduction to a 30 percent increase relative to those from petroleum fuels.[85]

In general, of all potential feedstock options, producing ethanol from corn results in the smallest decrease in overall emissions. The greatest benefit, meanwhile, comes from ethanol produced from sugar cane grown in Brazil (or from using cellulose or wood waste as feedstock, as discussed later in this chapter).[86] Several studies have assessed the net emissions reductions resulting from sugar cane ethanol in Brazil, and all have concluded that the benefits far exceed those from grain-based ethanol produced in Europe and the United States. Kaltner et al. (2005) estimate that the total life-cycle GHG emissions reductions associated with Brazil's ethanol industry are equivalent to 46.6 million tonnes annually (12.75 million tonnes of carbon per year), or approximately 20 percent of Brazil's annual fossil fuel emissions.[87]

Fulton et al. (2004) attribute the lower life-cycle climate impacts of Brazilian sugar cane ethanol to two major factors: First, cane yields are high and require relatively low inputs of fertilizer, since Brazil has better solar resources and high soil productivity. Second, almost all conversion plants use bagasse for energy, and many recent plants use co-generation (heat and electricity), enabling them to feed electricity into the grid. As such, net fossil energy requirements are near zero, and in some cases could be below zero.[88] (In addition, less energy is required for processing because there is no need for the extra step to break down starch into simple sugars. Because most process energy in Brazil is already renewable, this does not really play a role.)

Table 11–1. Estimated Change in Life-Cycle Greenhouse Gas Emissions per Kilometer Traveled by Replacing Gasoline with Various Ethanol Blends[a]

Feedstock and Blend (country or other specifics, where available)	Emissions Change (percent)	Source
Corn		
E10 (United States)	-1	M. Wang et al. (1999)
E10 (China)	-3.9	M. Wang et al. (2005)
E85 (United States)	-14 to -19	M. Wang et al. (1999)
E85 (China)	-25	G. Wang et al. (2005)
E90 (United States, 2010)	*+3.3*	*Delucchi (2005)*
E95 (United States, 1999)	-19 to -25	M. Wang et al. (1999)
E100	-13	Farrell et al. (2006)
E100	-21	Marland et al. (1991)
E100 (wet-milled)	-25	M. Wang (2001)
E100	-30 to -33	Levy (1993)
E100 (dry-milled)	-32	M. Wang (2001)
E100	-38	Levelton (2000)
Sugar Beet		
E100	-35 to -56	Levy (1993)
E100 (N. France)	-35[b] to -56[c]	Armstrong et al. (2002)
E100	-41	GM et al. (2002)
E100	-50	European Commission (1994)
E100	-56	Wuppertal (2005)
Molasses		
E10 (Australia)	-1 to -3[d]	Beer et al. (2001)
E85 (Australia)	-24 to -51[d]	Beer et al. (2001)
Sugar Cane		
E100 (Hydrous; Brazil)	-87 to -95	Macedo et al. (2004)
E100 (Anhydrous; Brazil)	-91 to -96	Macedo et al. (2004)
Wheat		
E100	-19	European Commission (1994)
E100	-32 to -35	Levy (1993)
E100	-45	Wuppertal (2005)
E100	-47	Gover et al. (1996)
E100 (UK)	-47	Armstrong et al. (2002)

Notes: (a) assumes use of current-generation ethanol fuels in conventional spark-ignition vehicles; (b) average case; (c) best case; (d) range depends on credits for co-products.

Source: See Endnote 81 for this chapter.

It important to note that using ethanol to make ETBE results in even greater GHG savings than blending ethanol directly with gasoline, according to Edwards (2005) and Quirin et al. (2004). This is because ETBE replaces MTBE, which has relatively high energy demand, whereas ethanol replaces gasoline, which requires less energy for production than does MTBE.[89]

11.3.2 Biodiesel

The range of estimates for GHG emissions reductions from biodiesel is also large. Most studies show a net reduction in emissions, with waste cooking oil providing the greatest savings.[90] (See Table 11–2.) The exception is Delucchi (2003), who estimates that biodiesel from soybeans will lead to significant emissions increases by 2015.[91] Depending on assumptions (including land use change), he believes that soy biodiesel could result in net emissions ranging from zero (relative to fossil fuels) to an increase of more than 100 percent.[92]

Table 11–2. Estimated Change in Life-Cycle Greenhouse Gas Emissions per Kilometer Traveled by Replacing Diesel with 100-Percent Biodiesel[a]

Feedstock and Country (other specifics, where available)	Emissions Change (percent)	Source
Rapeseed		
Germany	-21	Armstrong et al. (2002)
Netherlands	-38[b]	Novem (2003)
	-40	Larivé (2005)
	-44 to –48	Levy (1993)
	-49	GM et al. (2002)
	-51	Scharmer and Gosse (1999)
Australia	-54	Beer et al. (2001)
	-56	ETSU (1996)
	-56 to –66	Scharmer and Gosse (1996)
	-58	Richards (2000)
	-68	Wuppertal (2005)
Pure plant oil		
Unspecified oil source	-42	Wuppertal (2005)
Soybeans		
United States (2015)	*+107*	*Delucchi (2003)*
Netherlands	-53[b]	Novem (2003)
	-63	Levelton (1999)
Australia	-65	Beer et al. (2001)
United States	-78[b]	Sheehan et al. (1998)
Tallow		
Australia	-55	Beer et al. (2001)
Waste Cooking Oil		

Australia	-92	Beer et al. (2001)

Note: (a) assumes current generation biodiesel used in conventional compression-ignition vehicles; (b) only CO_2 emissions are considered. Source: See Endnote 90 for this chapter.

Other studies show major reductions in emissions from soybean diesel. Larson (2005) found that estimates for emissions reductions from soy methyl ester (SME) are similar to those for rapeseed methyl ester (RME), which provides a 15–65 percent reduction per vehicle kilometer traveled.[93] Again, varying results are due to different assumptions, as described above.

11.3.3 Summary of Life-Cycle Impacts

The production and use of biofuels, per se, does not necessarily result in a net reduction in GHG emissions relative to petroleum fuels. However, most studies have found that the majority of biofuel feedstock-to-fuel pathways, with existing commercial technologies, have a solidly positive GHG balance. The higher the blend of biofuels to conventional fuels, the greater any savings in GHG emissions will be.

According to Larson (2005), conventional grain- and oilseed-based biofuels can offer only modest reductions in GHG emissions. The primary reason for this is that they represent only a small portion of the above ground biomass. He estimates that, very broadly, biofuels from grains or seeds have the potential for a 20–30 percent reduction in GHG emissions per vehicle-kilometer, sugar beets can achieve reductions of 40–50 percent, and sugar cane (average in southeast Brazil) can achieve a reduction of 90 percent.[94]

Quirin et al. (2004), meanwhile, considered both current and future vehicle technologies, and used 2010 as their time reference. They looked only at studies that included methane, N_2O and CO_2; analyzed impacts of all relevant agricultural sources (fertilizer production and emissions from field); and accounted for co-products. Their conclusion is that the GHG emissions balances of all biofuels considered are favorable compared to fossil fuel counterparts.[*] More specifically, they found that: ETBE has advantages over all other biofuels; whether ethanol is better than biodiesel depends on the feedstock used; and biodiesel from rapeseed is favorable to pure rapeseed oil because the glycerin co-product can be substituted for technically produced glycerin.[95]

In general, the viability of biofuels as low-carbon replacements for oil depends less on the amount of energy required in production than on the type of energy used—assuming the same system boundaries (e.g., no land-use changes and the same level of final output). Corn-derived ethanol, for example, may indirectly emit as much fossil carbon into the atmosphere as gasoline if the corn is grown with nitrogen fertilizers derived from petroleum sources; irrigated, harvested and delivered with vehicles run on conventional fuel; and processed using energy generated from coal. If, however, the corn is grown with manure or other natural fertilizers, harvested and delivered with biofuels, and distilled with renewable power, the associated life-cycle emissions could drop to near zero.[96] This highlights the importance of choice of feedstock, selection of

[*] Biofuels considered included ethanol from sugar cane, corn, wheat, sugar beets, potatoes, molasses, and lignocellulose; ETBE from wheat, sugar beets, potatoes, and lignocellulose; biodiesel from rapeseed, sunflowers, soybeans, canola, coconut oil, recycled vegetable oil, animal grease, and used cooking grease; vegetable oil from rapeseed and sunflower; biomass-to-liquid (BTL), biomethanol, DME, and hydrogen from lignocellulose; biogas from organic residues and cultivated biomass; and hydrogen from organic residues.

refining processes, and carefully planning and designing the entire biofuel pathway, integrating it into the context of the biomass energy system.[97]

11.4 Reducing the Climate Impact

In the future, there is the potential to further reduce GHG emissions associated with biofuels, through a variety of means. These include improved yields with existing feedstock, improved process efficiencies, new energy crops, new technologies, and an increase in co-product development.

11.4.1 Improved Yields with Existing Feedstock

Over the past several decades, significant yield improvements have been achieved with a variety of crops—from sugar cane and corn, to soybeans, oil palm, and willow—and advances are expected to continue.[98] Yield increases are due to several factors, including breeding (particularly hybridization), genetic improvement, better farming practices, and farming conservation measures.[99] (See Chapter 6.) Yields for miscanthus, switchgrass, and other energy grasses are expected to increase significantly as well. So far, energy crops such as switchgrass and poplar trees have not been bred intensively, and some experts believe that breeding could result in a doubling of their productivity.[100]

As crop yields improve, the amount of land and other inputs required to produce a given amount of biofuel decline, generally reducing the climate impact. (See Chapter 12 for other potential environmental implications.)

11.4.2 Improved Process Efficiency

Advances in technology and process efficiencies offer the potential for additional reductions in associated carbon emissions. Improvements to date have been significant, as seen in both the United States and Brazil.

Over the past 30 years, the U.S. ethanol yield per bushel of corn has increased steadily, from less than 9 liters (2.4 gallons) per bushel in the 1970s to between 9.8 and 10.6 liters (2.6 and 2.8 gallons) by the mid-2000s. This represents an efficiency increase of 8–16 percent; where one falls in this range depends on the starch content of the corn and process efficiency.[101]

In Brazil, the improvements have been even more significant. Fulton et al. (2004) note that the ethanol yield from one tonne of sugar cane increased 23 percent between 1975 and 2002, from 73 liters per tonne in 1975, to 85 liters in 1995 and 90 liters in 2002. The best values are 10–20 percent higher than average, and it is expected that these will become the average over the next several years.[102] According to other sources, the increase in yield, due to technological innovations and efficiency improvements, has been far greater. Nastari (2005) estimates a near tripling over the past 30 years, from about 2,000 liters of ethanol per hectare of sugar cane in 1975, to 5,000 liters in 1999 and 5,900 liters in 2004, for an average annual increase of 3.8 percent.[103] Some put the current yield as high as 7,000 liters per hectare under good conditions.[104]

A study by the Dutch Energy Agency (NOVEM) and Arthur D. Little (ADL) estimated that life-cycle CO_2-equivalent emissions would decline significantly for many processes by the 2010–

2015 period, with most pathways leading to high reductions relative to gasoline or diesel. In many cases, GHG emissions reductions would exceed 100 percent, due mainly to the use of biomass for process energy. They projected that the greatest reductions would result from production of cellulosic ethanol using enzymatic hydrolysis in biorefineries, but that biomass gasification and conversion to final fuels such as diesel and DME would provide similar reductions.[105]

While Quirin et al. (2004) project that the GHG benefits of biofuels will increase with time, they also note that higher conversion efficiencies will mean fewer co-products, reducing advantages somewhat.[106] In addition, it will be important to ensure over time that the benefits from technological progress are not outweighed by the rising costs of obtaining an ever-growing supply of feedstock through unsustainable means—such as replacing tropical forests with palm oil plantations.

11.4.3 New Energy Feedstock

Improvements in technologies and process efficiencies could bring about significant further reductions in emissions, but they will not be enough to change relative benefits of given types of biomass and land-use changes.[107] Such improvements might also have difficulty counterbalancing the negative impacts of expanding feedstock supply, and associated land use, if not sited, selected, planted, and managed in a sustainable manner.

Thus, it is important to focus on new energy crops, such as short-rotation forests and perennial grasses, which offer significant potential for further reducing the life-cycle emissions of biofuels. Such crops, if planted in place of annual crops or on degraded lands or unimproved pasture, can increase standing biomass growing above ground and the amount of biomass under ground and, hence, carbon sequestration.[108] Despite their current lower ethanol yields, at least one study has determined that making ethanol from hay and switchgrass results in some of the lowest life-cycle GHG emissions because these crops sequester carbon in the ground—assuming they are grown on unimproved pasture or in place of annual crops.[109] Because these perennial energy crops also generally require less fertilizer and less irrigation than other feedstock crops do, they effectively reduce CO_2 emissions associated with the final product (biofuel).

The use of short-rotation forestry and logging residues on forest land (the tops and branches that remain after trunks are harvested at felling sites) can reduce GHG emissions relative to other feedstock crops because the trees increase carbon sequestration in the soil and their biomass, and N_2O emissions drop because of the reduced use of fertilizers. However, Börjesson and Berndes caution that the recovery of logging residues can result in higher emissions than if the branches and other residues are left to decay on site.[110] More research may be needed to determine the life-cycle impacts of such practices. (See Chapter 12 for more on the impacts of residue removal.)

Technological advances that enable the use of cellulosic and other feedstock—including animal manure, the organic portion of municipal wastes, and waste restaurant grease—could dramatically reduce the life-cycle GHG emissions associated with some biofuels while providing the added benefit of reducing the amount of land and other resources required to store or dispose of these products. Quirin et al. (2004) argue, however, that alternative uses of waste materials must be considered when determining life cycle impacts of using them as biofuel feedstock (e.g., for BTL); studies to date have ignored this issue.[111]

11.4.4 Advanced Technologies

New technologies under development offer the potential to dramatically increase yields per unit of land and fossil input, and further reduce life-cycle emissions. Cellulosic conversion processes for ethanol offer the greatest potential for reductions because feedstock can come from the waste of other products or from energy crops, and the remaining parts of the plant can be used for process energy.[112] (See Table 11–3.)

Table 11–3. Estimated Change in Life-Cycle Greenhouse Gas Emissions per Kilometer Traveled by Replacing Gasoline with Ethanol from Cellulose[a]

Feedstock (country or other specifics, where available)	Emissions Change (percent)	Source
Wheat residue (straw)	-57	Levelton (2000)
Corn residue (stover)	-61	Levelton (2000)
Hay	-68	Levelton (2000)
Grass	-37.2 -66 to -71 -71 -73	Delucchi (2005) GM/ANL (2001) Levelton (2000) Wang (2001)
Waste wood (E85; Australia)	-81	Beer et al. (2001)
Crop residue (straw)	-82	GM et al. (2002)
Wood Poplar tree	-51 -107	GM et al. (2002) Wang (2001)

Note: (a) in conventional spark-ignition vehicles.
Source: See Endnote 112 for this chapter.

Larson (2005) projects that future advanced cellulosic processes (to ethanol, F-T diesel, or DME) from perennial crops could bring reductions of 80–90 percent and higher.[113] According to Fulton et al. (2004), net GHG emissions reductions can even exceed 100 percent if the feedstock takes up more CO_2 while it is growing than the CO_2-equivalent emissions released during its full life cycle (for example, if some of it is used as process energy to offset coal-fired power).[114] Delucchi, too, believes that next-generation feedstock (such as switchgrass and poplar) and processes can result in substantial reductions compared with petroleum fuels, assuming that all major production processes and the use of fertilizer inputs become more efficient, and that biomass is used as process energy.[115]

Typical estimates for reductions from cellulosic ethanol (most of which come from engineering studies, as few large-scale production facilities exist to date) range from 70–90 percent relative to conventional gasoline, according to Fulton et al. (2004), though the full range of estimates is far broader.[116] Where exactly cellulosic ethanol falls in such a range depends on the feedstock used to produce it, assumptions regarding fertilizer input, end-use efficiency of vehicles, and co-products.[117] Wang et al. (1999) estimate that cellulosic ethanol made from woody biomass (such as poplar trees) can achieve reductions larger than those from herbaceous biomass.[118]

A number of other advanced technologies are also being developed to convert biomass into gaseous and liquid fuels for vehicle use. As mentioned earlier, a NOVEM-ADL study estimated life-cycle CO_2-equivalent emissions that might be typical for a variety of processes by the period

2010–2015. They projected that cellulosic ethanol made using enzymatic hydrolysis in biorefineries would provide the greatest reductions, followed by biomass gasification.[119] (See Table 11–4.)

Table 11–4. Estimated Change in Life-Cycle Greenhouse Gas Emissions per Kilometer Traveled by Replacing Gasoline or Diesel with Advanced Biofuels (2010–2015)

Fuel	Feedstock/Location	Process	Emissions Change (percent)
Diesel			
Biodiesel	Rapeseed (local)	Oil to FAME (transesterification)	-38
Biodiesel	Soybeans (local)	Oil to FAME	-53
Diesel	Biomass-eucalyptus (Baltic)	HTU biocrude	-60
Diesel	Biomass-eucalyptus (Baltic)	Gasification/F-T	-108
Diesel	Biomass-eucalyptus (Baltic)	Pyrolysis	-64
DME	Biomass-eucalyptus (Baltic)	Gasification/DME conversion	-89
Gasoline			
Gasoline	Biomass-eucalyptus (Baltic)	Gasification/F-T	-104
Ethanol	Biomass-poplar (Baltic)	Enzymatic hydrolysis	-112
Ethanol	Biomass-poplar (Brazil)	Enzymatic hydrolysis	-112
Ethanol	Biomass-poplar (local with feedstock from Brazil)	Enzymatic hydrolysis	-101
Ethanol	Corn (local)	Fermentation	-72

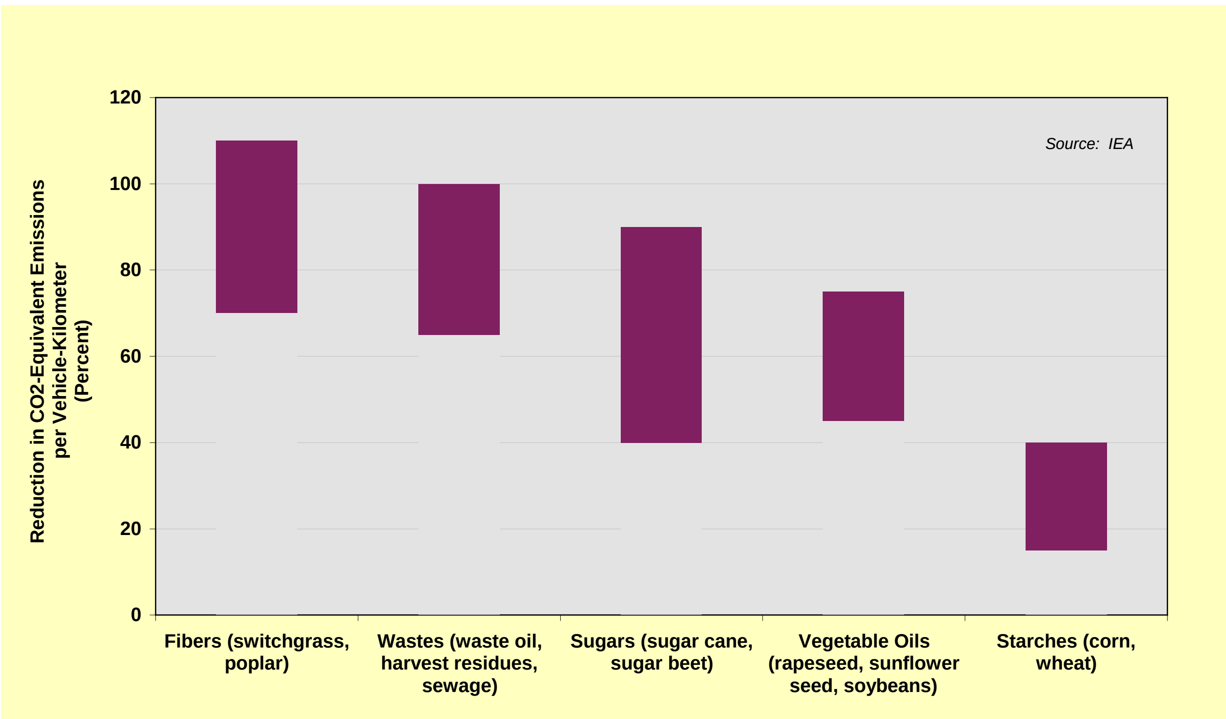
Source: See Endnote 119 for this chapter.

The company Genencor has developed a new kind of alpha amylase enzyme that dramatically reduces the temperatures required for processing corn starches—from 105–150º Celsius (C) to 32º C.[120] This "no-cook" hydrolization process could significantly reduce energy input requirements, thereby reducing emissions directly or increasing the amount of excess renewable energy that can be fed into the local electric grid.

High-oil algae colonies offer a potentially large source of feedstock for biodiesel that could result in significant emissions reductions. While precise numbers are disputed, it is believed that algae can produce far more oil per hectare than any other biodiesel feedstock, and can do so even in deserts. Significant emissions reductions could be possible particularly if agricultural waste streams or power plant emissions are used to feed the algae.[121] (See Chapter 4.)

Hydrous, anaerobic pyrolysis, which mimics the geological conditions that created crude oil, can use “wastes” that other industries must dispose of (often at cost). The process releases few GHGs, largely because the conversion process does not oxidize organic matter.[122] Changing World Technologies, based in the United States, claims to use the same feedstocks for process energy and fuel.[123] And gasification followed by Fischer-Tropsch (F-T) synthesis (also called biomass-to-liquid, or BTL), which uses carbon-fixing perennial plants, can reduce GHG emissions by more than 100 percent, if the process is powered by the biomass feedstock, and if the feedstock is perennial plants that sequester carbon, or wastes. It can also convert lignin into liquid fuel—something that cellulosic processes cannot do.[124] (See Chapter 5.)
Figure 11–1 shows the range of estimated possible reductions in emissions from wastes and other next-generation feedstock relative to those from current-generation feedstock and technologies.[125]

Figure 11–1. Reductions in Greenhouse Gas Emissions per Vehicle-Kilometer, by Feedstock and Associated Refining Technology



Yet another possible means for improving the GHG benefits of biofuels is carbon capture combined with storage. According to Faaij (2005), during the fermentation process, about half the biomass in sugar and starch rich sources is converted into ethanol and the remainder is converted into CO_2. And, with regard to F-T production, about half the carbon in the original feedstock can be captured before conversion of syngas to F-T fuels. CO_2 capture and storage during these processes could allow for negative emissions per unit of energy produced on a life-cycle basis.[126] Larson (2005) also projects that this option would enable reductions to exceed 100 percent.[127]

11.4.5 Co-products

As discussed above, the production of additional co-products can reduce GHG emissions as well. In particular, renewable lignin from energy crops can reduce or eliminate the need for coal or gas required for processing, directly reducing GHG emissions. If excess electricity is available to feed into the local utility grid, offsetting fossil-generated power, resultant emissions reductions could be even greater.

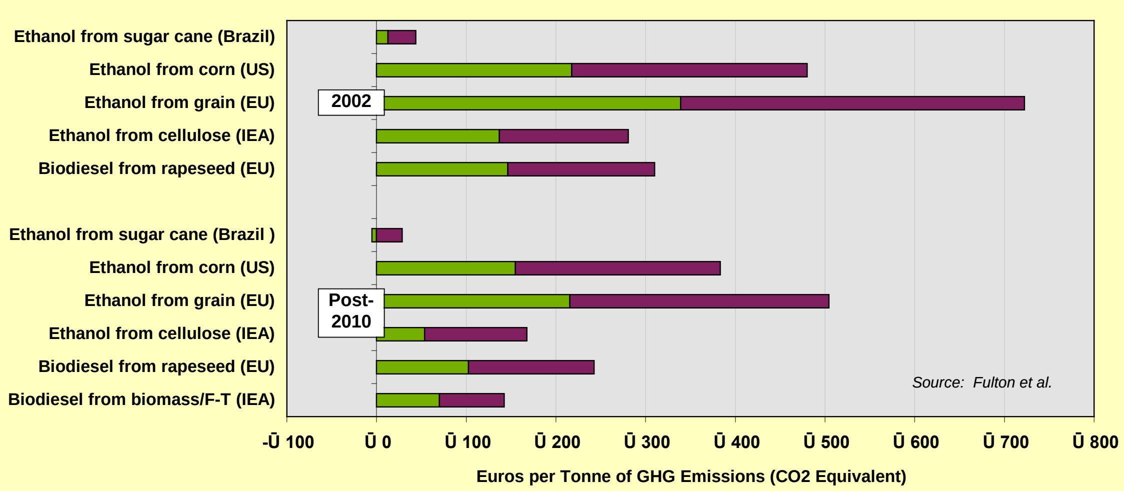
11.5 Trade-offs

Despite the potential climate-related benefits associated with biofuels, and the major role that the transport sector plays in the production of global GHGs, many experts have questioned the wisdom of converting biomass to transport fuels if the primary aim is to reduce global warming gases. They cite costly emissions reductions relative to other options, and note that land and biomass resources would be more efficiently used for other purposes.

11.5.1 Economic Costs

Biofuels are currently a relatively expensive means of reducing GHG emissions relative to other mitigation measures, according to analyses from many countries, with the cost of CO_2-equivalent emissions reductions exceeding €135 per tonne ($163/tonne), according to estimates analyzed by Fulton et al. (2004).[128] (See Figure 11–2.) The one exception is Brazil, where pure ethanol sold for nearly 40 percent less than the gasoline-ethanol blend in late 2005 (even accounting for the lower energy content in ethanol).[129]

Figure 11–2. Biofuel Cost per Tonne of Greenhouse Gas Reduction



Note: Ranges were developed using highest cost/ lowest GHG reduction estimate, and lowest cost/ highest GHG reduction estimate for each option, then taking the 25% and 75% percentile of this range to represent the low and high estimates in this figure. In some cases, ranges were developed around point estimates to reflect uncertainty.

Even within the transport sector, there are several more cost-effective options for reducing carbon emissions, including investments in and promotion of public transportation, increased use of bicycles and other non-motorized vehicles, improvements in vehicle fuel-efficiency, and changes in urban planning and land use. Not only could such measures provide larger reductions at lower costs, but they are also of strategic importance for many developing nations, where demand for transport is increasing rapidly.[130]

Several studies in the European Union have concluded that GHG emissions savings from fuel ethanol, based on domestic production using wheat and sugar beets, have cost a minimum of €200 ($242) per tonne of CO_2—about ten times the marginal abatement cost in the EU emissions trading scheme of €20 per tonne.[131] Larivé (2005) notes that, even with oil at €50 per barrel ($60.5 per barrel), there are no biofuels options that cost less than €100 per tonne of CO_2 avoided.[132] Compare this to the Kyoto Protocol's Clean Development Mechanism which, according to a World Bank report, provides carbon market prices of less than €8 ($10) per tonne of CO_2 and an expected maximum price of €12.4–16.5 ($15–20) per ton of CO_2 over the coming decade."[133]

Other studies have noted that using biomass to produce combined heat and power is currently a far more cost-effective means for reducing GHG emissions than converting it to biofuel. And a 2003 study prepared by Mortimer et al. for the UK Department of Environment, Food and Rural Affairs concluded that biofuel is one of the most expensive options for reducing CO_2 emissions from biomass. Its authors estimated that the greatest savings, of all options considered in the report, comes from the use of glass-fiber loft insulation which, for the same amount of money, could reduce CO_2 emissions by 92–141 times more than was possible using biodiesel from oilseed rape, and by 24 times more than was possible heating with wood chips from short rotation coppice.[134*]

At the same time, the CO_2 avoided by using biofuels is only a part—albeit a significant part—of the societal benefit derived from these fuels. It is important to note that many options exist to substitute for coal in the generation of heat and electricity, *but biofuels offer the only realistic near-term option for displacing and supplementing liquid transport fuels*. Assuming oil prices remain high, the economic advantages of replacing oil for transport as opposed to fossil electricity will increase as well.

Further, the long-term costs for next-generation biofuels—such as F-T biodiesel or cellulosic ethanol—could be significantly lower than production costs are today, making biofuels more cost competitive as a means to reduce GHG emissions.[135] Today, biodiesel from oilseed crops is quite expensive to produce, but it can outperform ethanol made from grains in terms of potential GHG reductions, and thus costs less per tonne of CO_2 avoided. Over the long term, however, fuels from lignocellulosic biomass have the greatest potential (of all fuels from biomass, including methanol, ethanol, hydrogen and synthetic diesel) for cost reductions.[136]

Hamelinck (2004) projects that these *next-generation biofuels, particularly cellulosic ethanol, could achieve abatement costs well below €41 per tonne ($50/tonne) of CO_2; with oil prices at €41 per barrel ($50 per barrel) or higher, biofuels are fully competitive and mitigation costs could actually be negative*.[137] The potential for such great cost reductions is the result of several

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[*] For every British pound spent, biodiesel from rapeseed (depending on the production process) could save 3.4–5.2 kilograms of CO_2, heat from short rotation coppice wood chips would save 18.2 kilograms, and glass-fiber loft insulation would save 478.5 kilograms of CO_2, per N.D. Mortimer et al., "Evaluation of the Comparative Energy, Global Warming and Socio-Economic Costs and Benefits of Biodiesel," prepared for the UK Department for Environment, Food and Rural Affairs (London: January 2003), p. ix.

factors: the feedstock can be grown on less valuable land, has lower energy requirements for cultivation and harvest, and has the potential for much higher energy yields per hectare.[138] It is also possible to move greater distances per hectare on cellulosic fuels than it is on fuels from rapeseed or sugar beet, a difference that will become greater with time.[139] Fulton et al. (2004) note that because it could bring down per-tonne costs of GHG reductions so dramatically compared to today's technologies, "supporting the use of a relatively expensive fuel that provides large emissions reductions, like cellulosic ethanol, may be worthwhile."[140]

Moreover, as global oil prices rise, biofuels will become more cost-competitive and could ultimately be less expensive than conventional transport fuels. As mentioned earlier, this has already been the case in Brazil. Where and when this occurs, the use of biofuels could actually save consumers money, meaning that the costs of reducing GHG emissions through the use of biofuels would be negative.

Finally, it is important to keep in mind the environmental and associated economic costs of non-biofuel alternatives to conventional petroleum fuels. Estimated reserves of unconventional oil from tar sands and oil shale in Canada and the United States, respectively, are far greater than combined proved reserves and estimated possible (undiscovered) reserves of conventional oil.[141] (See Chapter 12.) By some estimates more than six times as much CO_2 is released per barrel of oil produced from oil sands than per barrel of conventional oil.[142]

11.5.2 Biomass and Land Resources

Several studies have concluded that, even aside from the more favorable economics of combined heat and power (CHP), CHP is the best option for reducing GHG emissions with biomass.[143] The biggest impact can come from using biomass resources to replace coal, rather than petroleum fuels. For example, Armstrong et al. (2002) estimate that using biomass as fuel to produce steam and electricity, or CHP, provides up to 200 gigajoules (GJ) of energy per hectare of land, compared to a maximum potential of 30–60 GJ per hectare from ethanol or biodiesel.[144] According to Graham, Wright, and Turhollow (1992), using cellulosic crops to produce ethanol provides about half the CO_2 reductions that could be achieved by using them to displace coal.[145]

Over the medium term (2020 and beyond), however, Faaij (2005) argues that using biomass to produce transport fuels may be a more-effective means for reducing GHG emissions than using biomass to generate power. "This can be explained by the partly observed and partly expected reduction in carbon intensity of power generation due to large scale penetration of wind energy, increased use of highly efficient natural gas fired combined cycles and deployment of CO_2 capture and storage (in particular at coal fired power stations)."[146]

Others recommend that, unless the goal is short-term reductions in CO_2 emissions, afforestation and reforestation measures should be considered before using land for the production and use of biofuels, or even electricity. Tampier et al. (2004) estimate that, over a 50-year period, "trees can sequester more carbon dioxide out of the air than can be displaced through transportation fuels or electricity from biomass."[147]

On the other hand, an International Energy Agency study notes that afforestation and forest protection are only conditional mitigation options that are "subject to future management regimes."[148] Afforestation is a temporary measure, whereas bioenergy can provide an irreversible mitigation impact. Schlamadinger and Marland argue that, over the long term (40 years or more), there is a relative advantage to using surplus agricultural land for biofuel production (and substitution of fossil fuels) rather than afforestation. They note that: "The net carbon advantage depends on the growth rate of the site and on the efficiency with which fossil fuel carbon emissions are reduced through the use of biofuels. Biofuel production is the better choice especially with efficient use of biomass and for high growth rates."[149]

Also in the future, cascading biomass over time—recycling biomass materials for various uses—can help to optimize the CO_2-mitigation effects of biomass resources. It is possible to displace more fossil fuel feedstock, and thus to derive a far greater carbon benefit, by using biomass for material production, such as plastics, and subsequently using that material (when it has reached the end of its useful life) for energy production. Dornburg and Faaij (2004) have studied in detail the climate and economic impacts of cascading biomass and conclude that this practice could provide CO_2 benefits up to a factor of five compared to biomass used for energy alone.[150]

11.6 Conclusion

A dramatic increase in the production and use of biofuels has the potential to significantly reduce overall GHG emissions associated with the global transport sector; alternatively, it could intensify the threat of a warming world. The overall climate impacts of biofuels will depend on several factors, the most important of which are associated land use changes, choice of feedstock and how it is managed (including its energy yield per hectare and level of fossil inputs), and the refining process (including co-product output and source of process energy). If, for example, perennial crops replace annual crops—such as corn now grown to produce ethanol—and are processed with biomass energy that offsets coal-fired power, the resulting biofuel can significantly reduce GHG emissions compared to petroleum fuels.

Alternatively, if prairie grassland is converted to corn or soy, treated with chemical fertilizers and pesticides, and refined with coal and natural gas, the resulting fuel could have a greater impact on the climate over its life cycle than do petroleum fuels. However, even "sustainable" energy crops can have a negative impact if they replace tropical forests, resulting in large releases of carbon from soil and existing biomass that negate any benefits of biofuels for decades. In general, crops that require significant energy inputs (such as fertilizer) and valuable farmland, and have relatively low energy yields per hectare, should be avoided.[151]

The greatest potential for reducing GHG emissions and associated costs lies in the development of next-generation feedstock and biofuels. In the future, next-generation technologies—advanced cellulosic technologies, in particular—offer the potential to reduce transport-related GHG emissions significantly. Assuming oil prices remain high, it will be possible to achieve negative CO_2-abatement costs in the process, while providing a host of other environmental and social benefits as well. Government policies should focus on commercializing these advanced technologies and driving down their costs as rapidly as possible.

Governments must also do whatever possible to protect virgin lands such as grasslands and forests, and to encourage the use of sustainable feedstock and management practices in order to minimize associated GHG emissions—indeed, such policies should extend beyond biofuel production to the agricultural sector in general. In addition, a certification scheme needs to be developed that includes GHG verification for the entire life cycle of biofuel products; it will be a challenge to find ways to implement such a scheme in a generally accepted manner, but this should not deter governments from making the effort. This is not the case in most countries today, and biomass is often automatically considered “carbon neutral” without accounting for upstream emissions. The United Kingdom is now contemplating a scheme for imported biofuels that includes the entire supply chain in emissions accounting, and Belgium has already put such a scheme into legislation.[152] (See Chapter 18.)

Further research is needed to fill gaps in the existing body of life-cycle studies, including more analyses that are locally relevant to developing countries, and studies that cover the range of the biofuel feedstocks and pathways (including biodiesel from palm oil or jatropha, for example). It is also essential to have a better understanding of the scale of N_2O emissions from feedstock production and their potential impact on the global climate, to attain a more accurate picture of the full impacts of feedstock production on emissions. And more studies are needed that consider the relative efficiency of land use, for “While GHG mitigation per-vkm [vehicle-kilometer] is an important measure, land use efficiency in achieving GHG reductions may be the most important consideration.”[153]

Finally, biofuels must be used to *replace* petroleum fuels rather than to supplement them. If biofuels are able to substitute for petroleum they can provide a far greater benefit to the global climate than if they are produced and burned simply to meet a share of the world’s rapidly increasing demand for transport fuel. In general, any plan to promote the production and use of biofuels on a large scale must be part of a broader strategy to reduce total energy use in the transport sector. In addition to ending subsidies for conventional fuels (and for unconventional petroleum fuels), governments must encourage the development of lighter, more fuel-efficient vehicles, and promote and support smarter urban design and mass transit.

Chapter 12. Environmental Impacts of Feedstock Production

12.1 Introduction

One of the greatest benefits of using biofuels is the potential to significantly reduce greenhouse gas emissions associated with the transport sector. One of the greatest risks, however, is the impact on land used for feedstock production, particularly virgin land, and the associated effects on habitat, biodiversity, and water, air, and soil quality. These concerns are particularly valid with current, first-generation feedstock. On the other hand, bioenergy production offers the potential to reduce the environmental load relative to conventional, industrialized agriculture, if farming practices are adjusted to maximize total energy yield rather than the oil, starch, or sugar contents of their crops, diversifying plant varieties and reducing chemical inputs.

In contrast to the environmental costs of fossil fuels on land and wildlife, the impact of biofuels on the landscape has been relatively small. But as production levels rise and as more nations increase their use of these fuels, the environmental tradeoffs seen thus far will likely be experienced on a far larger scale. This creates an urgent need for developing biofuels in a more environmentally sustainable manner.

This chapter discusses the main environmental issues associated with the production of biofuel feedstock. For comparison, it first briefly discusses some of the environmental costs associated with obtaining petroleum-based fuels. It then examines the costs and benefits—to the land, water, and air—of generating biomass feedstock for biofuels.[*] (The chapter does not address climate change issues, which are discussed in Chapter 11.)

12.2 Environmental Costs of Oil Exploration and Extraction

Crude oil represents a fraction of 1 percent of ancient biomass that has been stored in vast quantities over tens of millions of years.[1] Locating it and then removing it from the ground can entail high costs to the landscape. The first step in extracting oil from the ground is finding deposits that are large and concentrated enough to remove profitably. This exploration not only requires the construction and use of large machines, but it involves drilling in sites that are sometimes in ecologically sensitive areas. Most of the holes drilled come up dry: historically, oil exploration companies drilled five holes for every "wet" one, while today the ratio is about one in three with the advent of 3-D seismic imaging.[2]

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[*] Notably, only a relatively small number of studies look at the overall impacts of biofuels, and most consider only single variables or steps along the entire pathway. In addition, many of these studies make conclusions based on observations that are location-specific, making it difficult to obtain a big picture view. Further, while numerous studies focus on the environmental impacts of commonly used biofuels such as ethanol and biodiesel, research on future fuels, like biomass-to-liquids, is lacking. See, e.g., Markus Quirin et al., "CO_2 Mitigation through Biofuels in the Transport Sector: Status and Perspectives, Main Report" (Heidelberg: Institute for Energy and Environmental Research, August 2004), and Eric D. Larson, "Liquid Biofuel Systems for the Transport Sector: A Background Paper," draft for discussion at the GEF/STAP (Global Environment Facility/Scientific and Technical Advisory Panel) Workshop on Liquid Biofuels, New Delhi, 29 August–1 September 2005.

The impact of the machinery used to extract petroleum itself is relatively small—the energy embodied in this machinery, and the energy used for pumping, compressors, etc., consumes only about 1 percent of the total energy it can process during its lifetime.[3] However, the processes required to extract "enhanced" oil from the ground with secondary and tertiary methods are more energy intensive, and can use more than 15 percent of the energy in crude oil. This includes the energy needed to drill deep, often dry, holes (usually diesel fuel); to construct concrete pipes to hold the hole open (coal and electricity); and, occasionally, to heat the underground oil deposits into a manageable liquid, and to inject chemicals, carbon dioxide (CO_2), or even steam (natural gas).[4]

On land, oil extraction can destabilize terrain and disrupt underground aquifers by removing large volumes of oil and methane from the ground. Land subsidence is common where oil has been extracted from soft, sandy formations. Oil drilling near the ocean, meanwhile, can suck salty seawater into freshwater aquifers: in the Gulf of Mexico, for example, coastal drilling has transformed uplands into wetlands, and wetlands into open water.[5] In addition, much of the water used to push oil out of reservoirs, once polluted, remains underground, where it is either treated onsite or simply cleansed by evaporation. But oil fields leak water-borne ions and chemicals into the surrounding ecosystems, particularly sodium, chloride, boron, benzene, and arsenic.[6]

Oil deposits often overlap with natural methane gas deposits. If nothing is done to prevent the methane's escape, it rises into the atmosphere, where it acts as a powerful greenhouse gas. Oil companies can burn it, releasing carbon dioxide (CO_2), or, if the proper infrastructure is available at the wellhead, they can contain it to use in the oil extraction process or sell.[7]

Drilling muds, formed from drill cuttings and containing toxic aromatic compounds, accumulate around the base of marine oil platforms. Where tidal currents are weak, cuttings remain intact to form large "cutting piles." In the deeper waters of the northern North Sea, these piles can contain as much as 40,000 tonnes of contaminated sediment, with devastating consequences for marine habitat in the surrounding areas. Adverse affects of the early muds, based on diesel oil, were found to extend out as far as 5 kilometers from the point of discharge. Less-toxic alternatives are now used where possible, and cuttings are generally re-injected down wells or removed for treatment on shore.[8]

Once crude oil reaches Earth's surface, it causes other environmental problems at the drilling site. Earlier production techniques did not contain oil once it was struck, and often "gushers" would last for hours or days, occasionally catching fire and spreading clouds of smoke and pollutants. Today, oil is usually—but not always—contained in the drill hole.[9] But smaller overflows continue during the lifetime of an oilfield. In jungle regions, extraction operations can be especially toxic for ecosystems and native lands.[10] Drilling offshore can result in the dredging of sensitive marine ecosystems, including coral reefs, and oil leaked directly into the ocean is far more difficult to contain.[11]

As oil prices rise, it is becoming more economical to extract oil from non-conventional resources, such as tar sands and oil shale. Estimated reserves of these unconventional petroleum fuels are enormous—Canada's oil reserves are considered second only to Saudi

Arabia's, but the environmental costs of extracting and using them are enormous as well.[12*] With Canadian tar sands, for example, about 20 percent of the resource is close enough to the surface that it is strip-mined. The largest such pit in Alberta is a 50-square-mile "moonscape" of slag heaps and tailing ponds. Once the pits are depleted, extraction involves reaching deeper deposits by pumping in steam to dissolve the thick oil so that it can be brought to the surface. This requires large amounts of both water and energy, and results in significant quantities of wastewater. The oily slurry that separates from grains of sand must then be refined to make usable oil, as discussed in Chapter 13. Two tons of this sand are required to produce a single barrel of oil.[13] Impacts on air quality are great as well, with both direct emissions from the mining process and indirect impacts associated with electricity generation.

Whether conventional or unconventional, oil exploration and extraction have negative impacts on wildlife and plant populations due to local pollution as well as the loss or fragmentation of habitats, and obstruction or elimination of migration routes that result from infrastructure (from roads to facilities to pipelines) required to access these fuels.[14] In the future, a greater share of the world's oil will also come from more remote areas—such as offshore, and the Arctic—which are more sensitive to disruption and pollution, and often the habitats of rare species.

12.3 Biofuel Feedstock Production and Land-Use Changes

The environmental problems associated with obtaining the feedstock for biofuels can also be serious—indeed, this is probably the most environmentally disruptive stage of biofuel production. However, the net environmental impact of land use for feedstock production on habitat, biodiversity, and soil, water, and air quality depends on a variety of factors, including the choice of feedstock, what the feedstock replaces, and how it is managed.

12.3.1 Threatening Wild Habitat

The impacts of agricultural land use practices for conventional crops can be dramatic, affecting everything from biodiversity to the global climate. The biggest threat posed by expanding the amount of land under cultivation for energy or any other use is the irreversible conversion of virgin ecosystems. Deforestation, for example, causes the annihilation of species and their habitats, and the loss of ecosystem functions. Studies reveal that wide-scale destruction of forests can affect the hydrologic cycle and the climate, reducing regional precipitation and increasing temperatures.[15]

Rising demand for biofuels is motivating the expansion of agriculture onto previously unexploited lands in some regions, and could cause intensification of land use in others. In the near term, the ecosystems at greatest risk include the rainforests of Malaysia, Indonesia, and Brazil, and the savannahs of southern Brazil. These regions are of great value due to their species richness, containing a large share of the world's diversity of flora and fauna. Also under

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[*] It is estimated that U.S. oil shale reserves total 2 trillion barrels, and Canadian tar sand reserves are 1.5 trillion barrels—far more than remaining proved and possible oil reserves from conventional sources, per Tony Dammer, Office of Naval Petroleum and Oil Shale Reserves, U.S. Department of Energy, "Strategic Significance of America's Oil Shale Resource," presentation at 2005 Energy Information Administration Midterm Energy Outlook Conference, Washington, DC, 12 April 2005.

threat are natural forests, grasslands, and wetlands, from rural England to Tanzania, which are homes to large numbers of mammals, songbirds, and wild plants.

Expanding into Brazil's Cerrado

Sugar cane in particular has a poor environmental track record. Over the past several hundred years, it has had as large an impact as perhaps any other agricultural commodity, with the greatest consequence being the loss of biodiversity.[16] This is particularly true in tropical regions such as the Caribbean, where diverse ecosystems were destroyed largely by sugar planted during early European colonization.

In Brazil, the cultivation of sugar cane for ethanol, and increasingly of oilseed crops for biodiesel, is occuring as agricultural pressure is also increasing to meet rising demand for sugar and soy in food and feed markets. The expansion of sugar cane production via large monocultures has replaced pasturelands and small farms of varied crops.[17] Plantations for sugar and ethanol production have expanded predominantly into areas once used for cattle grazing, as cattle move on to new pastureland (often cleared rainforests).[18] In the future, the *cerrado*, a largely wild central savanna that covers more than one-quarter of Brazil's land area, is considered the natural expansion area for sugar cane production.[19] The cerrado is home to half of Brazil's endemic species (found nowhere else on Earth) and a quarter of its threatened species. Expansion of agricultural production into the region's complex ecosystems could result in irreversible ecological damage.[20]

A similar trend is occurring with soybeans, which are replacing vast stretches of both wild cerrado and rain forest. Over the decade between 1994/5 and 2004/5, Brazilian soybean production nearly doubled, from 11.7 million hectares to 22.3 million hectares.[21] Many of the country's large soybean plantations have been developed by acquiring smaller plots of land with more varied crops, while about half of the nation's soybean crop has moved into cerrado in the middle-west region, where climate and soil are considered suitable for cultivation.[22]

Expanding into Rain Forests

The cerrado is not the only Brazilian ecosystem at risk. In the state of Mato Grosso do Sul, in the country's southwest, the state assembly is debating the construction of ethanol plants along the upper Paraguay River. The river runs through the Pantanal, the world's largest wetland area, and there is concern that plant construction will threaten the environmental balance of this delicate ecosystem.[23] As transportation infrastructure advances towards Brazil's Amazon region to facilitate the flow of soybeans, sugar cane, and other products to processing facilities and ports in the east, it is more likely that these crops will expand into sensitive areas where they are not currently economically viable.[24]

Already, rain forests from Brazil to Southeast Asia are being cleared to grow soybeans and palm oil.[25] While these crops are now produced primarily for food rather than fuel, they are being used increasingly to produce biofuels for transportation and electricity.[26] Their cultivation adds to the predominant forces of deforestation in the Brazilian Amazon, which are cattle ranching and illegal timber cutting.[27] According to Schneider et al. (2000), increased soybean production is triggering the expansion of pastureland for cattle into new forest areas, which is considered "one of the main causes of tropical deforestation in the Brazilian Amazon."[28] To date, nearly 20 percent of the Amazon, home to an estimated 30 percent of the world's species of plants and animals, has been burned or otherwise destroyed, much of it due to large-scale agriculture.[29]

Palm oil expansion, meanwhile, is one of the "leading causes" of rainforest destruction in Southeast Asia and "one of the most environmentally damaging commodities on the planet," according to Simon Counsell, director of the UK-based Rainforest Foundation. Palm plantations are expanding rapidly in eastern Malaysia as well as in Indonesia— where, despite laws prohibiting clearing for palm oil plantations, natural forests are being felled at a rapid pace.[30] Rather than planting on abandoned agricultural land, palm oil producers are instead expanding into forestland, a more attractive prospect since recently cleared forests need less fertilizer and the timber can be sold for capital.[31]

This expansion poses a tremendous threat to the region's biodiversity, including endangered megafauna such as tigers, Asian elephants, and the Sumatran rhinoceros.[32] According to the environmental organization Friends of the Earth, palm oil plantations in Indonesia and Malaysia are the primary cause of the decline of the world's orangutans and could drive the species to extinction within the next 10 years.[33] Environmentalists and other groups in Europe, particularly in the United Kingdom and the Netherlands, have expressed concern that rising EU demand for biofuels could accelerate this deforestation, undermining the environmental benefits sought through policies to promote these fuels.[34]

The palm oil industry has noted that there is far more biodiversity in palm oil plantations than in fields of annual grains, vegetables, and other short-term crops because palm oil trees are perennial crops cultivated in tropical areas.[35] This is relevant, however, only if palm oil plantations replace these crops, not wild forests. (For information regarding the Roundtable on Sustainable Palm Oil, formed to address concerns related to palm oil production, see Chapter 18.)

Expanding into Cropland, Wild Lands, and Conservation Reserve Land

While expansion of biofuel crops into tropical forests might be the greatest land-use concern due to potential effects on biodiversity, biofuel expansion could cause problems elsewhere as well. In the United Kingdom, for example, feedstock production could threaten the diversity in farmland uses and might have a detrimental impact on the nation's bird population.[36] In Tanzania, as in many other countries, there is concern that biomass crops could replace existing forest or grasslands, and that small farms of varied crops could be replaced by large tracts of monoculture plantations.[37] In the United States, rising demand for soybeans and corn could increase the "duo-culture" cropping style that already dominates much of the Midwest.

Expansion of the corn-ethanol market in the United States also threatens to put millions of acres of conservation reserve land back into production, increasing erosion and eliminating many of the wildlife benefits realized since the reserve program began. Much of this land was put into reserve in the mid-1980s because its rough, sloping ground makes it difficult to plant.[38] In 2004, the European Commission estimated that 5 percent of EU transport fuel needs could be met by growing energy crops on currently unproductive agricultural lands, while forests, grassland, and the use of wastes could provide yet more.[39] The EU is now considering sustainability impacts of these plans, and even the possibility of expanding nature conservation areas; thus, the potential biofuels resource base will likely be reduced.[40]

Given the possible threats to both land and wildlife, it will be necessary to carefully manage the risks associated with use of set-aside lands. The tradeoff is not necessarily easy: as demand for biofuels increases, if feedstock crops are not produced in the United States and Europe, then they will simply be cultivated elsewhere, leading to potential landscape and ecosystems effects in other regions.

Fortunately, as crop yields continue to increase, land requirements per liter of biofuels (and possible water and other requirements as well) will decline, along with related impacts on habitat and wildlife. To date, many first-generation energy crops have been bred for their starch or oil content, not for their leaves, stems, or other resources; there has been little to no effort to optimize plants for mass, a trait that is far easier to manipulate. Aggressive breeding programs could significantly increase yields of cellulosic feedstock, such as corn stover or switchgrass for next-generation biofuels, without the use of genetic modification.[41] Further, crops that are bred specifically for energy content may require less fertilizer and pesticide.[42] Another important option, for next-generation biofuels, will be to grow short-rotation woody crops and other perennial plants instead of annual crops, thereby increasing yields while reducing chemical inputs and overall environmental impacts.

But some efforts to improve crop yields could have a cost. If use of fertilizers and other inputs are increased, for example, GHG emissions will rise and other negative impacts result. Plant breeding that selects only the most-productive crops can be done at the cost of genetic diversity (though cross-breeding can increase diversity), bringing a greater susceptibility to disease.[43] And genetic engineering, while offering the potential to increase yields, remains controversial, with concerns about possible cross-pollination and other long-term effects.[44] (See Sidebar 12–1.)

Sidebar 12–1. Benefits and Costs of Genetically Modified Crops

Genetically modified (GM) crops are being developed and used increasingly in the United States and elsewhere because of the desire to increase yields and reduce the need for water and pesticide. As of 2003, about 80 percent of the U.S. soybean crop and 40 percent of its corn crop were genetically modified, and GM rapeseeds and sugar beets are now available as well. Use of GM crops is increasing elsewhere as well, although there is considerable opposition to them in much of the world, including in several European countries and much of Asia.

Among possible benefits of GM crops, studies cite the potential for higher yields (even under difficult growing conditions), qualitative improvements in crops, and diversification of plant uses. According to some reports, the use of RoundUp Ready soybeans (engineered to tolerate potent herbicides that previously would have destroyed crops along with weeds) has reduced the need for herbicide and increased yields by as much as 10 percent, while reducing soil erosion by up to 50 percent because the lack of weeds makes it easier to employ no-till farming methods.

Others contend that RoundUp Ready soybeans have hurt crop yields, and that the appearance of more-resistant strains of weeds has increased per-hectare rates of glyphosate (herbicide) use. According to Benbrook (2004), chemical use has increased with the introduction of GM organisms. While Bt crops (resistant to specific insect pests) may have reduced insecticide use somewhat, herbicide tolerant crops have actually increased herbicide use much more substantially (after an initial reduction). Scientists at the Minnesota-based Institute for Agriculture and Trade Policy note that use of GM crops only helps to prevent yield decreases in years with very specific infestations. They also note that no-till adoption has been flat for several years in the United Sates, and there is no evidence that RoundUp Ready crops have increased its use. Additionally, there is concern that the use of GM crops accelerates negative effects on plant biodiversity that already existed due to monocultural farming and pest and weed resistance.

Any benefits of GM crops must be weighed carefully against the risks they pose to wildlife, wild and organic plants, and human health. One three-year study in the United Kingdom, completed in 2003 (the largest then-undertaken), demonstrated that GM crops have severe implications for wild birds. The government panel involved in the study concluded that, while there was not enough evidence to predict long-term impacts, the potent herbicides used on GM crops posed an unquantified risk to wildlife. Scientists linked the potential risk to the way GM crops were sprayed: spraying GM sugar beets caused more damage to the environment than spraying conventional sugar beet varieties. Further, GM herbicide-resistant rapeseed had the same number of weeds overall as conventional rapeseed, but more grass weeds and fewer broad-leaved weeds, whose seeds are an important food source for wildlife.

The same study concluded that GM and other crops might not be able to coexist because of potential contamination, and that future GM generations could pose new risks. Ecologists have expressed concern that GM plants might breed with wild relatives, altering their identity or even creating fast-growing "superweeds" with increased resistance to some pesticides. Studies in the United States and Europe have shown that the potential exists for genes to flow from GM crops (including oilseed crops) into wild populations because of historical hybridizations and the movement of pollen. Two separate UK studies found that bees carrying GM pollen from rapeseed had contaminated conventional plants more than 26 kilometers (16 miles) away. And a 2002 U.S. survey by the Organic Farming Research Foundation found that up to 80 percent of organic farmers in the Midwest (where millions of hectares of GM crops are grown) reported direct costs or damages associated with GM contamination, which disqualified their products as organic.

Others contend that GM crops could accelerate the pesticide treadmill—whereby pervasive cultivation and spraying of herbicide-tolerant crops could build resistance in weeds, requiring ever-increasing applications of herbicide and introducing hardier weed varieties into the environment. Other impacts can include the killing of important soil organisms, and dangers to human health due to increased pesticide use. A recent report from the Africa Centre for Biosafety and Friends of the Earth Nigeria linked intensive cultivation of GM soybeans in Latin America with decreased soil fertility and increased soil erosion and deforestation. In Argentina, according to a local NGO, the consequences of growing GM soybeans include "a massive exodus [of people] from the countryside and ecological devastation." Air spraying of pesticides (particularly glyphosate) on RoundUp Ready soybeans has destroyed other crops, killed farm animals, and caused human illnesses ranging from allergies to vomiting and diarrhea.

Genetically modified industrial microorganisms (GMIOs), created to flourish under manufactured conditions (such as high temperatures) rather than in nature, will likely play a significant role in future biofuel development—particularly in the fermentation of carbohydrates to manufacture cellulosic ethanol. But because GMIOs would likely have a competitive disadvantage in the wild, there is less opposition to them than to GM crops. Even the German Green party supports the use of GMIOs, while continuing to oppose GM crops. However, there remains the potential that these organisms might pose a yet-undetermined threat to the environment, making testing and the development of appropriate safeguards essential.

Sources: See Endnote 44 for this chapter.

12.3.2 Minimizing Land Use and Wildlife Impacts

Despite the multiple risks posed to land and habitat by production of biofuel feedstock, many options exist for minimizing these costs or even improving biodiversity. One possibility is to expand onto degraded lands that cannot currenty support agriculture; another is to use agricultural and forest residues and wastes as feedstock, a practice that is possible today only on a small scale, but that offers significant potential when processing and biofuel conversion technologies are further developed.

Expanding onto Marginal Lands

Over the short term, India plans to cover 400 thousand hectares across several hundred districts—approximately 0.13 percent of the nation's land area—with jatropha plantations.[45] This is not expected to affect plant or animal biodiversity, as the bushes will be planted on current wastelands. However, no studies have been done to date to determine any potential biodiversity impacts, and The Energy Resources Institute (TERI) (2005) notes that there is concern that once India moves beyond the initial demonstration phase and increases the scale of jatropha and pongamia plantations, this could interfere with the nation's natural forest ecosystems.[46]

Jatropha is also being used in African countries like Mali to reverse desertification while providing income and a new source of fuel for both electricity and transport.[47] The benefits of jatropha and pongamia are discussed in greater detail elsewhere in this chapter and report.

Greater Land Efficiency of "Next-Generation" Feedstock

Oil seed and starch crops grown in temperate areas use land inefficiently and can require large amounts of fertilizer and pesticides. But tropical oil and sugar plants, which are more land efficient and need fewer chemical inputs, can also raise environmental concerns, primarily because they can expand into wild habitats. And all biomass crops are of concern if they are grown in monoculture habitats and/or with genetically modified organisms. However, there exists the potential to dramatically increase the land efficiency of biofuel feedstock.

The best option for reducing land use and related impacts is commercializing the production of cellulosic ethanol, as well as gasification technologies to produce biofuels from woody biomass, and waste products, using Fischer-Tropsch synthesis. (See Chapters 4 and 5.) Cellulosic feedstock could represent a significant improvement over conventional feedstock. The "wastes" are essentially free, residues can be extracted from land that is already under cultivation, and perennial energy crops can provide a more diverse habitat for wildlife. They provide better ground cover, improving the soil and water retention. And they can yield a greater quantity of fuel per hectare than sugars, starches, or vegetable oils, meaning that they use the land far more efficiently.[48]

Cellulosic technologies will enable the use of agricultural and forest residues not just as process energy (as bagasse is now used in Brazil), but also as feedstock for biofuels. However, it is important to note that, unlike other residues, residues from forests do not create "waste" problems if they are not removed and used, because they are recycled naturally. However, more research is needed to determine how much can safely be "harvested" without affecting soil quality.

Additionally, many cellulosic energy crops, such as perennial grasses or woody biomass, offer greater diversity and variability in biofuel products and can be grown economically on less valuable land, and with fewer inputs.[49] These crops could potentially be grown in place of food crops (assuming they are no longer needed for food) that are now used to produce biofuels, such as the increasing share of U.S. cropland that is used to grow corn for ethanol, or the rapeseed, sugar beets, wheat, and sunflower that is grown in Europe for the production of biodiesel. It will be critical to focus such efforts on native species of grasses that are appropriate for the soils and climate where they are planted, and to avoid the potential for invasive species, such as kudzu, to take over crops and natural areas.

Suitable crops vary from one climate or region to another. One challenge will be to find more biomass crops that are appropriate for use in more arid regions, such as the Mediterranean region. At this point it appears that most perennial crops are not suited for production in very dry summers without irrigation, or that they increase fire risk where this is already a serious threat—though this might be mitigated through appropriate timing of wood harvesting.[50]

Advanced technologies offer other options as well. Some experts believe that oil-rich micro-algae can be grown on a massive scale atop buildings and even in deserts and used to produce biodiesel, with the remainder after pressing used as animal feed and ethanol feedstock.[51] Between 1978 and 1996, the U.S. National Renewable Energy Laboratory sponsored an Aquatic Species Program that focused on the potential to produce biodiesel from high-lipid algae. The Program's final report estimated that 28.4 billion liters (7.5 billion gallons) of biodiesel could be produced on 200,000 hectares of desert land; producing that amount of biodiesel from rapeseed would require nearly 117 times that much land and, of course, rapeseed cannot be grown in the desert.[52]

In addition, waste products such as waste oils, restaurant grease, and the organic part of municipal solid wastes can be converted into fuel, saving valuable land area that might otherwise be used for landfills. To give a sense of the potential scale, New York City alone produces enough garbage to fill a hectare of landfill in fewer than 10 days.[53] Converting this to biofuels could potentially result in a significant amount of fuel while saving land and money. It is estimated that just converting U.S. agricultural waste into oil and gas would result in the equivalent of 4 billion barrels of oil each year, or nearly 13.6 percent of global oil consumption in 2004.[54] And as discussed in Chapter 5, there already exist technologies to process animal wastes and carcasses into fuel.

Benefits of Next-Generation Feedstock for Wildlife

Despite the enormous ecological costs that could potentially come from increasing production of biofuels feedstock, some crops under some circumstances can actually encourage increased wildlife populations and diversity—particularly perennial crops that provide a stable environment, are well-managed, and replace existing annual crops (such as corn or rapeseed) or are planted on marginal lands.[55] In fact, the limited studies done to date suggest that the more-stable environment provided by perennial crops can increase population sizes and diversity of birds, small mammals, and soil fauna.[56]

A study by the Wisconsin Department of Natural Resources in the United States found that switchgrass (a prairie grass native to North America) has the potential to provide high-quality nesting cover for many grassland bird species currently in decline.[57] When the grass was harvested for bioenergy production, suitable habitat remained for a number of birds, particularly species that prefer short- to medium-height vegetation. Maintaining some unharvested areas within the field would permit habitat for birds that prefer tall vegetation.

But even more-sustainable energy crops like woody crops and switchgrass cannot substitute for natural forests or prairies, and they cannot support the same mixture of bird and small mammal species that would be found there.[58] Further, perennial crops such as short-rotation tree plantations might be no better for biodiversity than annual crops if large tracts of monocultures replace numerous small fields of a variety of annual crops.[59] However, they can serve some of the functions of these natural systems and can enhance regional biodiversity if planted in landscapes dominated by annual crops, as long as they do not displace an important food source provided by the original land use.[60]

In general, as one study has noted, “the effect of biomass plantations on biodiversity may depend as much on how they fit into the landscape as on the particular species and management systems selected.”[61] For example, biomass crops can benefit wildlife if they are used as buffers along waterways and between forests or natural grasslands and annual crops, or as protective corridors that allow plants and wildlife to move from one natural area to the next.[62] Tree plantations sited alongside natural forests can expand the habitat for forest bird species, even in regions dominated by agriculture.[63] Intercropping with grasses and trees can help to maintain diversity of plants and animals (or at least reduce loss) on energy plantations, while also reducing soil erosion.[64] Patches of vegetation left because of less-frequent mowing or rotational harvesting also result in greater diversity and abundance of small mammals.[65] And the creation of forests and grasslands that are structurally and species diverse can help to reduce the negative impacts of weeds, insects, and diseases.[66]

12.4 Effects on Soil Quality

In general, when land is converted from natural cover to intensive annual crop production, the organic matter content of the soil decreases over time. The use of chemical fertilizers to add nutrients back into the soil and pesticides to deal with weeds, insects, and blights reduces soil biodiversity. Use of nitrogen fertilizers also causes acidification of soils and surface waters. According to the United Nations Environment Programme, these problems are increasingly caused by nitrogen emissions in industrial countries, as sulfur emissions are brought under control.[67] Intensive farming also causes soil erosion, which is especially a problem in areas with prolonged dry periods followed by heavy rains, and with steep slopes and unstable soil, such as the Mediterranean.[68] Erosion causes a loss of organic soil substances, and the resulting nutrient losses can cause eutrophication in nearby surface waters, affecting other plants and wildlife.[69]

Soil impacts during feedstock harvesting depend on both the intensity of the activity and the length of crop rotation periods. Intensive harvesting methods can compact the soil (which affects soil structure and biodiversity and can cause water logging), deplete soil nutrients and organic matter, and affect the soil’s capacity to hold moisture; short crop rotation periods, meanwhile reduce soil fertility.[70] Soil exposed during and after harvesting is vulnerable to erosion, so frequency of harvesting and replanting are significant in determining environmental impact.

On some soils, the removal of crop residue can reduce soil quality, increase associated GHG emissions through the loss of soil carbon, and promote erosion; thus, the amount that can be removed sustainably varies by crop type. There is evidence that residue removal changes the rate of physical, chemical, and biological processes in the soil, by causing more fluctuations in soil temperatures and increased water evaporation. These changes, in turn, affect crop growth. One study estimates that corn-derived soil organic carbon is reduced by 35 percent when residue is harvested versus when it is retained; this is averaged over all tillage systems.[71]

12.4.1 Soil Quality Benefits of Perennial Energy Crops

Where perennial energy crops such as some trees or native grasses replace annual crops, they can improve soil quality in a variety of ways, including increasing soil cover (and thus reducing erosion), reducing soil disturbance, improving organic matter and carbon levels in soil, and increasing soil biodiversity. This is particularly true if application of inputs such as fertilizers and pesticides are reduced, and if crops provide year-round soil cover.[72]

Tree plantations can provide many benefits. For instance, there is evidence that plantations of some tree species can reduce evaporative water losses and improve soil moisture conditions to allow for cropping on previously degraded lands. Tree species that fix nitrogen, such as leaucaena and acacias, can reduce the need for nitrogen fertilizer while improving soil quality and producing food for farm animals.[73]

Oilseed trees, like jatropha or pongamia, require little input or rainfall and can thrive in infertile soil. High-yield wild jatropha varieties have been found in Mexico and Mali.[74] Pongamia trees flourish in dry areas with poor or saline soils, including much of Asia, the Middle East, and many islands in the Pacific and Indian Ocean, and produce a high oil yield while improving soil quality.[75]

Tree leaves can add organic matter and improve soil fertility and physical properties, and tree cover can protect land from water and wind erosion.[76] Short-rotation coppice (SRC) could reduce erosion even more if cover crops are used during the first two growing seasons to stabilize soils.[77] The positive effects trees have on the soil's ability to retain water improve with time, so longer rotations are preferable from that standpoint.[78] Palm trees can also protect soil from erosion and can be grown in poor soils, establishing tree cover fairly rapidly and mimicking tropical rainforest, according to one report.[79]

A 1987 study by Pimentel and Krummel estimated that erosion from SRC is one order of magnitude less than that from row crops, and erosion from hayland (or switchgrass) is one order of magnitude less than for SRC.[80] Perennial grasses, which have extensive root systems and do not require tilling, and plantations with some species of trees (including jatropha and pongamia) can not only reduce soil erosion but also help increase soil productivity. They can also reduce the need for chemical inputs and water, compared with more-intensive crops like corn, wheat, and soybeans. Such crops can often grow on marginal or erosion-prone lands, reduce chemical runoff, and provide good habitat for wildlife. This is especially true if they are allowed to grow for several years before being harvested.[81]

12.4.2 Sustainable Management and Harvesting Practices

Achieving a sustainable biofuels industry—including sustainable cellulosic ethanol based on crop residue—will require management practices that maintain long-term soil productivity and reduce chemical inputs. Conservation tillage and no-till planting—which involve the use of machinery that injects seeds directly into the soil, thus avoiding the plowing of fields—have become more common for some crops in the United States, Brazil, and Europe. Their use can reduce soil erosion and the leaching of fertilizer, while saving the energy required for plowing fields.[82] Using a cover crop between rows of trees further reduces the potential for erosion.

Switchgrass also provides erosion control, but is most beneficial after it has become established.[83]

Germany has seen successful results with a new farming practice called “double cropping.” The fundamentals of this system include at least two crops and two harvests annually on the same field, no plowing, year-round ground cover, little-to-no chemical pest management (weeds can also be used as feedstock), and the use of fermentation residues for closed cycling of nutrients.[84] Mixing of crops (varieties, heights, etc.) can be beneficial by helping to reduce the need for nutrient inputs, enhance diversity of landscapes and crops, reduce the use of heavy machinery and water, and create year-round coverage, minimizing negative impacts on soils.[85] Importantly, crop mixing also preserves and enhances the diversity of crop species and can provide shelter and food for a larger variety of wildlife species than does the use of single crops.[86] As mentioned earlier, diversity also reduces susceptibility to pests (thereby reducing need for pesticides) and disease.[87]

Further, the use of intercropping, crop rotation, and bio-fertilizers can help recirculate nutrients in the soil that are lost through the growing and harvesting of crops like sugarcane and sweet sorghum.[88] In Brazil, it was expected that long-term cultivation of sugar cane would reduce soil productivity; however, the opposite has proved to be true, most likely due to good soil preparation, superior varieties of sugar cane, and recycling of nutrients through the application of vinasse (the nutrient rich water waste left over from sugar milling and ethanol distillation).[89] In addition to vinasse, nutrients can be returned to the fields via ash produced during processing (assuming it does not include toxins that are absorbed by some plants while growing, and that could become concentrated in soils).[90]

When crops are harvested, organic matter and nutrients can be maintained in the soil if sufficient biomass is left to conserve nutrients and organic matter (e.g., if only a small portion of branches and treetops are removed in short-rotation forests, and a portion of crop residue is allowed to remain in agricultural fields).[91] It should be noted that, while some agricultural residue is safe to remove for biofuels feedstock use, it is important to leave some on the ground to minimize soil loss and runoff. Numerous field studies analyzed by Benoit and Lindstrom (1987) suggest that a 30 percent removal rate would not significantly increase soil loss under a no-till system. However, they found that no-till without residue cover could allow more soil erosion than conventional tillage, while no-till with residue cover usually results in less soil erosion.[92] In general, sustainable crop residue removal rates depend on a variety of factors, including yield, management practices, and soil type.[93]

Similarly, in forests, logging residues reduce exposure of the soil to sun, wind, or rain, lowering the risk of erosion. Deadwood and residues also help to regulate water flow through forests, and are increasingly seen as important for protection of biodiversity. Thus, it is important to leave tree roots in the ground and some of the branches as mats to protect the soil. Residues and deadwood are also important sources of nutrients. Generally, the lowest concentration of nutrients is in wood and the highest is in tree foliage, so the rate of extraction and degree to which foliage remains on site play a major role in determining forest health.[94]

Other factors that can affect soil quality include the frequency of residue removal and the degree of tillage.[95] Because soil is more likely to be disturbed or compressed by heavy harvesting machinery when it is wet, farmers can also reduce damage by minimizing the use of heavy machinery and harvesting when the soil is dry or frozen.[96] In addition, winter harvesting of trees reduces soil nutrient loss because the leaves are not removed.[97]

12.5 Water Use and Pollution

Worldwide, the agricultural sector accounts for an estimated 70 percent of global freshwater use, and as much as 90 percent of water resources in some developing countries, much of it for highly inefficient irrigation.[98] As with agricultural production for food purposes, the growing of most feedstock for today's biofuels affects water supplies in two main ways: first, large amounts of water are required for feedstock production, potentially depleting valuable fresh water resources, and second, the runoff of agrochemicals and other waste products can pollute nearby waterways, threatening wildlife and speeding eutrophication.

12.5.1 Water Use for Irrigation

Cultivation of sugar cane, in particular, is highly water intensive. However, a recent World Bank report notes that water use in Brazil's sugar cane industry is declining, in part due to the creation of a legal framework to establish charges for water use. This is due primarily to reduced consumption in São Paulo, where most of the country's cane is grown; in fact, water use for sugar cane production is gradually increasing in other regions of Brazil.[99]

Heavy water use during dry spells, which occur often in Brazil and many other countries, intensifies water shortages and damages river ecosystems.[100] Irrigation also results in soil loss and leaching of nutrients and agrochemical residues from the soil.[101] As demand for biofuels increases, water consumption will only rise where feedstock crops are grown.

12.5.2 Water Quality Issues

Feedstock production also affects water quality, primarily through runoff of chemical inputs. Corn requires more pesticides than other food crops, and corn hybrids need more nitrogen fertilizer than any other crop. Runoff from these chemicals can find its way into the groundwater, causing contamination and affecting water quality.

Typically, less than half the nitrogen applied to crops in the form of fertilizer is actually taken up by the plants; the remainder is dissolved in surface waters, absorbed into groundwater, or lost to the air. [102] Eutrophication (rapid plant growth in water that results in oxygen deprivation) of surface waters from excess nitrogen runoff is a major concern, as is pollution from chemical pesticides. In the U.S. Midwest, the nation's corn belt, chemical runoff enters the Mississippi River and is carried to the Gulf of Mexico, where it has "already killed off marine life in a 12,000 square mile area," according to writer Michael Pollan.[103] (For more on the impacts of fertilizer and pesticide use, see Sidebar 12–2.[104])

Sidebar 12–2. Impacts of Fertilizer and Pesticide Use

The environmental impacts of fertilizer and pesticide use are many and varied, affecting everything from air quality and climate, to human and animal health, to the health of waterways and soils. Despite these problems, use of these chemical inputs continues to rise worldwide.

Nitrogen (N) fertilizer is generally made from natural gas, and pesticides are made from oil. Not only is fossil energy required to produce these chemical inputs, but it is also needed for their transportation and application, resulting in emissions of CO_2 and a host of other pollutants.

Inorganic N fertilizer accounts for about 60 percent of total anthropogenic nitrogen, which contributes to both climate change and ozone depletion. According to the U.N. Environment Programme, “There is a growing consensus among researchers that the scale of disruption of the nitrogen cycle may have global implications comparable to those cause by disruption to the carbon cycle.”

Fertilizer application rates vary depending on crop, soil type, temperature, and other factors. For instance, palm oil requires less fertilizer per unit of output than other oilseed crops. According to the U.S. Department of Agriculture, fertilizer makes up about 45 percent of the energy required to grow corn, despite the fact that the use of fertilizer for grain production has declined since the early 1980s. Fertilizer inputs are highest for oilseed rape, sugar beet, wheat, corn and potatoes, and generally lowest for non-wheat cereals, soy, linseed, and sunflower.

The use of nitrogen fertilizer results in emissions of nitrogen oxides, which lead to acidification and eutrophication. As production of first-generation feedstock crops increases, and drier, less fertile areas are increasingly used, the demand for irrigation and chemical fertilizers will rise. While some crops can expect improved yields through the development of hybrids, they will likely require more nitrogen fertilizer and pesticides as well.

In addition to polluting groundwater and water bodies, pesticides can kill beneficial soil and wildlife species and cause damage to neurological, reproductive, and endocrine systems in humans and wildlife. According to the World Health Organization, as many as 220,000 people die each year from pesticide poisoning, and millions more suffer from mild to severe affects of poisoning annually.

By 2000, corn growers in the United States were using 20 times more pesticide than they did in 1950, while also losing twice as much of their crop to pests. Bt (*bacillus thuringiensis)* corn, a genetically modified plant, was introduced in 1996 to address this problem, but it will likely only continue the pesticide treadmill (in which pests become resistant, requiring the use of more pesticides). By 1997, eight insect pests were already resistant to Bt corn.

Sugar cane also requires a significant amount of pesticide (in the form of herbicide)—about the same amount as soybeans, and even more herbicide per hectare than corn. Almost all cane farmers in Brazil have switched to no-till practices, which improve soil quality and reduce erosion, but also increase weed pressure over time. As a result, the use of chemical herbicides has risen, along with the number of herbicide-resistant weeds, forcing farmers to rotate crops and try to control weeds through mechanical means, but also to increase their toolbox of herbicide varieties.

Chemical inputs for feedstock can be reduced in a variety of ways. In Brazil, the use of chemical fertilizers has declined significantly due to regulations that control their use and the recycling of vinasse and filter cake into fertilizer. Fertilizer use can also be reduced through a careful matching of application with soil type and yields, and through careful timing and placement. Although most dedicated energy crops also require pesticide (particularly herbicides in the early years, to control weeds) and fertilizer inputs, research thus far suggests that needs are low relative to annual crops. Some crops do better with organic manure than with petroleum fertilizer. Jatropha can be fertilized with the de-oiled cake that remains after oil is expelled from the seeds.

Insecticide use can be significantly lowered for some crops through a variety of strategies including crop rotation, manual operations, and optimal selection of species. For example, in the

United States, 97 percent of corn receives herbicide treatments; but application rates decline to less than 25 percent with crop rotation, and to under 5 percent when corn is grown in rotation with small grains. Pesticide use has also reportedly declined in the Brazilian sugar cane industry, due to genetic developments of sugar cane species. And in India, although studies have not been done to determine the amount of pesticides that might be required for jatropha and pongamia plantations, jatropha oil itself has been used as a biodegradable pesticide in some parts of the country.

Where pesticides and fertilizers are used, trees and perennial grasses can act as filters of agricultural chemicals when they are planted between annual crops and waterways. Another option altogether is to shift to production of cellulosic ethanol, the feedstock for which—ranging from corn stover and rice bagasse to forest residue and municipal waste—requires few if any additional chemical inputs.

Source: See Endnote 104 for this chapter.

12.5.3 Reducing Impacts on Water

Careful crop selection can affect both water use and quality, by reducing the need to irrigate, and lowering if not eliminating the need for chemical fertilizers and pesticides—meaning that the water draining from their soils will have lower concentrations of chemicals.[105] Further, some crops can filter the nutrients that leach off adjacent farmland, ensuring that they do not reach nearby water bodies. Thus, the use of perennial crops and no-till buffer zones near waterways can reduce the biological and chemical oxygen demands generally placed on watercourses in agricultural areas.[106]

In addition, crops that are well managed can regulate water flows and reduce the risk of floods and droughts. This is particularly true for woody crops that are harvested over long periods of rotation.[107] The large leaf area of most woody crops, which is maintained for more of the year than leaves of annual crops, combined with their deeper root systems, can increase evapotranspiration and reduce the potential for runoff and leaching.[108] Another study suggests that growing such crops over large areas could improve water storage in dry regions.[109]

On the other hand, there is also the potential for negative impacts on local and regional hydrology from the introduction of energy crops. A 2001 study by Lyons et al. found that short-rotation coppice in southeast England actually increased the interception and use of rainfall, reducing rainfall infiltration and causing negative impacts on regional aquifers.[110] This is an issue that requires further study.

As mentioned earlier, plants such as jatropha and pongamia can be grown in arid and semi-arid areas on marginal lands. Yet even these crops require irrigation in some regions, and irrigation could increase yields in most locations. The need for irrigation can place additional pressure on already scarce water resources. In India, it is expected that jatropha plantations will need to be irrigated once monthly during the summer for the first 2–3 years after planting.[111] However, if such plants replace more water-intensive feedstock crops, there is the potential that water demands per unit of fuel could decline significantly. An added benefit of some oilseed crops like jatropha, and other perennial energy crops, is that they tend to require fewer chemical inputs than annual feedstock crops. As a result, they have far less impact on water *quality* than do annual grain and oilseed crops such as rapeseed, soybeans, and corn.[112]

12.6 Air Quality and Atmosphere

The most significant sources of local and regional air pollution associated with biofuels occur during combustion. (See Chapter 13.) But air quality is also affected somewhat during the feedstock growing process; for instance, farm machinery, which runs mainly on diesel, can cause a small amount of air pollution during planting and harvesting. In general, however, harvesting does not have a significant affect on air quality.

The only exception is when crops are intentionally burned to remove sharp tips and leaves that hinder access to the fields, as is standard practice in most sugar cane-growing countries.[113] This burning releases a host of gases and toxic compounds, including CO_2, carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), and nitrogen oxides (NO_x), which affect local and regional air quality.[114] Parts of Brazil, for example, have been blanketed with huge clouds of black smoke during harvest season.[115] Fires in cane fields have also occasionally spread to other areas, destroying native vegetation.[116]

To address such problems, the governments of Brazil (1998) and the Brazilian state of São Paulo (2002) have passed laws requiring a gradual phase-out of field burning and a transition to mechanical harvesting, though only São Paulo is currently enforcing the timetable.[117] In 20 percent of Brazil's sugar cane fields, cane trash left in the field is no longer burned; instead, much of it is deposited in the field where it can help maintain soil quality.[118]

Feedstock production also has a significant impact on the world's atmosphere, due to the use of inorganic nitrogen fertilizer, which accounts for 60 percent of anthropogenic nitrogen (N), as well as the cultivation of an increasing amount of leguminous crops such as soybeans, which account for about 25 percent of anthropogenic N. Not only is nitrogen oxide a potent greenhouse gas, but it also contributes to ozone depletion.[119]

12.7 Conclusion

The greatest environmental risks associated with biofuels result from the production of feedstock, with its derivative impacts on habitat, biodiversity, and soil, air and water quality. Fortunately, many of the concerns about water use and quality can be mitigated by using water more efficiently and recycling more of it for fertilizer, or digesting it for biogas. Problems with water availability and use, however, may represent a limit on the production of biofuels. Air quality problems associated with feedstock production are relatively minor, and can be reduced through measures such as shifting from petroleum diesel to biodiesel for farm machinery, and through regulations that limit or eliminate practices such as field burning.

Ultimately, it is the problems associated with the use of land, particularly virgin land, that will remain the most vexing and that deserve the most attention. As with agricultural crops grown for food, use of large-scale monocrops grown for energy purposes could lead to significant devastation of tropical forests and other wildlands, a loss of biodiversity, soil erosion, and nutrient leaching. Even varied and more sustainable energy crops could have negative impacts if they replace wild forests or grasslands. And eutrophication of water bodies, acidification of soils and surface waters, and ozone depletion, all associated with nitrogen compounds from agricultural production, are impacts of major concern. In fact, some studies have found that these three impacts are the greatest disadvantages of biofuels when compared with petroleum fuels.[120]

At the same time, new dedicated energy crops and sustainable resource management practices offer the potential for environmental improvements. Biofuels can have negative or positive effects on land use, soil and water quality, and on biodiversity, depending on the type of crop grown, what it is replacing, and methods of cultivation and harvest.

Feedstock selection is critical. Dedicated energy crops that are appropriate to the regions where they are planted—such as native perennial trees and grasses—can minimize the need for chemical inputs, avoiding some of the pollution associated with feedstock production, while also reducing water needs and providing habitat for birds and other wildlife. Oil seed bushes such as jatropha and pongamia can help to reduce desertification and restore degraded lands in countries from Mali to India. In the future, next-generation technologies that rely on agriculture and forest residue, or other forms of waste, could significantly reduce land requirements for biofuels production. More research is needed to determine how much residue can be safely removed to avoid degrading soil quality and reducing yields.

In addition, sound agricultural methods can achieve increases in productivity with neutral or even positive impacts on the surrounding environment, depending on the feedstock choice and what it is replacing. A variety of management practices, such as the use of intercropping, crop rotation, double cropping, and conservation tillage, can reduce soil erosion, improve soil quality, reduce water consumption, and reduce susceptibility of crops to pests and disease—thereby reducing the need for chemical fertilizers and pesticides. Using perennial crops as protective buffers or wildlife corridors can reduce chemical runoff and provide habitat for a variety of mammals and birds.

While there are great challenges to address, models do exist for ways to mitigate many of the risks associated with feedstock production. To address concerns about biodiversity loss, for example, the Brazilian state of São Paulo requires that sugar cane producers set aside 20 percent of their total planted area as natural reserves.[121] The palm oil industry in Southeast Asia has promoted wildlife sanctuaries and green corridors to enhance biodiversity.[122] These efforts are supported on the international level by the Roundtable on Sustainable Palm Oil, formed in 2004 to respond to rising concerns about the environmental impacts of oil palm plantations. (See Chapter 18.) In India, which has more than 300 species of oil-bearing trees, a multi-species biodiesel program could help to ensure plant genetic diversity.[123]

There is still a dire need for environmental policies and regulations at the local, national, and regional levels, particularly in developing countries, to ensure that impacts on land, wildlife, and water, air, and soil quality are minimized. For example, payment systems for water should be enacted to encourage more-efficient use and the growing of crops that minimize water consumption. Large-scale feedstock producers must be required to set aside a share of their land as natural reserve, as São Paulo has done, and other lands should be designated for low-intensity farming. Farmers need to be educated and given the proper resources and incentives to select crops appropriately and to manage them in the most sustainable ways possible, such that wildlife habitat is maintained or improved and the use and impacts of chemical inputs are minimized. Governments should also encourage the use of degraded lands for feedstock production, and encourage the planting of crops that have longer rotation periods, such as perennial grasses, while discouraging (if not banning) the use of virgin lands.

To date, most studies looking at the impacts of feedstock production have been species- and context-specific, so more research is needed to determine which management practices are most effective and least harmful to wildlife and surrounding ecosystems under different and broader circumstances. In addition, more research is needed in a variety of areas, including: the potential for using natural pesticides and fertilizers on feedstock crops; the potential impacts of large-scale plantations of oil-bearing trees, such as jatropha; the potential to increase crop yields while reducing inputs; the impacts of residue removal from cropland and forests, and how much can be safely harvested; and possible perennial feedstock that are suitable for arid regions. It is also critical to conduct further research to determine if the benefits of GM crops can outweigh their costs.

Over time, it is likely that the advantages of biofuels relative to petroleum fuels will increase as new feedstock and technologies are developed, and crop yields increase. It is important to get to this future as soon as possible by moving forward quickly to commercialize next-generation technologies, such as cellulosic ethanol and Fischer-Tropsch diesel from gasified biomass, that rely on less-resource-intensive feedstock. Furthermore, careful land-use planning and appropriate farming practices can establish safeguards against harmful biofuel cropping. At the same time, it is critical to develop international standards and certification systems to ensure that biofuels around the world are produced using the most sustainable methods possible. (See Chapter 18.)

It will be impossible to avoid all of the negative impacts of biomass production, at every location. Biofuels per se are not environmentally preferable to petroleum fuels—and again, their relative benefit is determined primarily by feedstock choice and management practices. Ultimately, the choice may be largely subjective, as decision makers weigh the merits and drawbacks related to different desired environmental ends—mitigating global climate change (which will likely affect entire species of plants and wildlife, as well as water resources, agricultural productivity, etc.), stemming the loss of species and landscapes, or improving air and water quality.

Chapter 13. Environmental Impacts of Processing, Transport, and Use

13.1 Introduction

The refining, transport, and combustion of biofuels can result in significant environmental costs, particularly on local water and air quality. Generally, however, these effects pale in comparison to those generated by the use of fossil fuels, where the main detrimental environmental effects originate from the vehicle tailpipe. Even so, these impacts could expand considerably as biofuel production increases to meet rapidly rising global demand. Here too, more-sustainable practices and new technologies offer the potential for environmental improvements.

This chapter examines the main environmental impacts associated with biofuels processing, transport, and use. To provide comparison, it first describes some of the environmental costs resulting from the processing and use of petroleum transport fuels. It then compares these with the (non-climate) environmental costs and benefits of biofuels at parallel stages of their life cycle.[*]

13.2 Environmental Costs of Petroleum Refining and Use

While the use of oil has brought incalculable benefits to modern industrial society, it has also exacted great costs, particularly to the local and global environments. Most of these occur during oil refining and fuel combustion. Delucchi (1995) estimated that in the United States, the costs of environmental externalities associated with oil and motor vehicle use totaled between €45 and €192 billion ($54 and $232 billion) in 1991 alone.[1] Human mortality and disease due to air pollution accounted for more than three-quarters of these costs, or as much as €152 billion ($184 billion) per year, according to the Union of Concerned Scientists.[2] In Germany, it is estimated that the quantifiable costs of air pollution and carbon dioxide emissions associated with the transport sector in 1998 totaled about €12 billion ($14.5 billion).[3]

13.2.1 Oil Refining

Refining petroleum is an energy-intensive, water-hungry, and highly polluting process. Every day, an average U.S. refinery releases 41,640 liters (11,000 gallons) of oil and other chemicals into the air, soil, and water.[4] People who live near these facilities have higher incidences of respiratory problems (including asthma, coughing, chest pain, choking, and bronchitis), skin irritations, nausea, eye problems, headaches, birth defects, leukemia, and cancers than the average population.

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[*] Notably, only a relatively small number of studies look at the overall lifecycle impacts of biofuels, and most consider only single variables or steps along the entire pathway, making it challenging to derive a big picture view. In addition, many of these studies make conclusions based on observations that are location-specific. Further, while numerous studies focus on the environmental impacts of commonly used biofuels such as ethanol and biodiesel, research on future fuels, like biomass-to-liquids, is lacking. See, e.g., Markus Quirin et al., "CO_2 Mitigation through Biofuels in the Transport Sector: Status and Perspectives, Main Report" (Heidelberg: Institute for Energy and Environmental Research, August 2004) and Eric D. Larson, "Liquid Biofuel Systems for the Transport Sector: A Background Paper," draft for discussion at the Global Environment Facility/Scientific and Technical Advisory Panel Workshop on Liquid Biofuels, New Delhi, 29 August–1 September 2005.

Crude oil, chemical inputs, and refined products leak from storage tanks and spill during transfer points. Numerous toxins are likely to enter the groundwater, including benzene (a toxic carcinogen), toluene (which debilitates kidney function, among other effects), ethylbenzene (a skin and mucous membrane irritant), and xylene (which likely inhibits development and leads to early death in exposed animals).[5] Other chemicals leak into the air. Gases like methane, and slightly heavier hydrocarbons such as those in gasoline, evaporate. Other chemicals enter the air as combustion products, the most significant of which are sulfur dioxide (SO_2), nitrogen oxide (NO_2), carbon dioxide (CO_2), carbon monoxide (CO), dioxins, hydrogen fluoride, chlorine, benzene, large and small particulate matter (PM), and lead.[6] Oil refineries are the largest industrial source of volatile organic compounds (VOCs) and CO, which lead to ozone and smog; the second largest industrial source of SO_2, which contributes to PM and acid rain; and the third largest industrial source of nitrogen oxides (NO_x), which are also ozone precursors.[7]

The refining process requires a great deal of energy, primarily in the form of natural gas and electricity. Petroleum refining accounted for 8 percent of total energy consumption in the United States in 1998.[8] And refineries consume significant amounts of water (typically 1.8–2.5 kilograms of process water for each kilogram of crude feedstock) and discharge between 1.7 and 3.1 times as much water as biofuel-processing facilities. Water consumption amounts to some 17,000–23,500 liters (4,400–6,200 gallons) per minute for a refinery that processes 100,000 barrels daily.[9] Water is also usually used to cool waste products distilled out from crude, to return them to liquid form. This water either evaporates or is released into surrounding ecosystems, where it can harm or eliminate species in streams or rivers.[10]

As mentioned in Chapter 12, unconventional oil resources like tar sands and oil shale are becoming more economical to extract and refine as oil prices rise. But their environmental costs are high as well. Once sands are extracted from the earth, they must be steam-cooked to separate the tarry residue and purify it. The heavy oil that is removed must be refined into lighter synthetic crude oil before it can be used.[11] The extraction and processing of tar sands requires about three barrels of water for every barrel of oil produced and result in large quantities of wastewater. Impacts on air quality are also large, with direct emissions including SO_2, CO, CO_2, NO_x, particulates, ozone, lead, silica, metals, ammonia, trace organics, and trace elements. Indirect air emissions result from generating the electricity required for extraction and processing. It is estimated that Shell's in-situ process for removing sands from deep within the ground and processing them would require as much energy as the end-use of the oil shale itself. The solid waste is significant as well: it is estimated that, for surface mining, 1.1–1.4 tonnes of spent shale must be disposed of for every barrel of oil produced.[12]

13.2.2 Oil Transport

Most of the world's crude oil comes from fields far from where it is refined and must be transported great distances from field to refinery, and from refinery to the fueling station. Large tanker vessels account for 68 percent of crude delivery to refineries, covering an average of 6,600 kilometers (4,100 miles) per trip. Oil pipelines, used mainly in places where deliveries can be land based, account for 30 percent, while trucks and trains transport the remainder.[13]

Invariably, oil spills occur along the journey. Although most tanker spillage is relatively minor (occurring during loading or unloading, or from slow leaks), even small amounts can damage ecosystems. The dramatic spill events that make the news, such as the Exxon Valdez spill off Alaska in 1989, account for only a small share of the crude oil spilled into marine environments, but they can have significant environmental impacts, including harming or killing local populations of coastal mammals, large numbers of water birds, and inter-tidal plant communities.[14] The Exxon Valdez spill cost an estimated €5.8 billion ($7 billion), including cleanup costs, with punitive fines representing €4.1 billion ($5 billion) of this total.[15]

Pipeline spills, though typically smaller, can also be ecologically disruptive, polluting soils and seeping into groundwater. Such spills can be fairly common in regions where pipelines are not maintained adequately: in Russia, for example, nearly 20 percent of oil leaks during transit, often into sensitive Siberian ecosystems, where it is too cold for the oil to evaporate or seep into the ground.[16] In conflict-ridden countries such as Colombia and Iraq, opposition groups have repeatedly blown up pipelines, spewing oil into jungle and desert ecosystems.[17]

Oil is shipped over great distances to refineries, and from refineries, gasoline and diesel fuels travel via pipelines and trucks to fuel depots. Upon leaving the refinery, 59 percent of refined petroleum fuels enter pipelines (which travel an average of 957 kilometers, or 595 miles), before being loaded into trucks. The other 41 percent goes straight into trucks, which travel about 60 kilometers (100 miles) to a commercial depot.[18] Along the way, gasoline and diesel fuels spill, contributing to the more than 50 percent of “oil spills” attributable to difficult-to-pinpoint urban runoff. Gasoline and diesel are lighter hydrocarbons that tend to evaporate, participating in the complex reactions that form ozone. Benzene, another evaporative air pollutant, is a known carcinogen. The most significant hydrological pollutant is methyl tertiary-butyl ether (MTBE), a fuel additive derived from petroleum that seeps quickly into nearby groundwater and is a likely carcinogen.[19]

13.2.3 Combustion of Petroleum Fuels

Compared to biofuels, petroleum contains a much wider variety of chemical molecules, including far more sulfur. Most of these have been sequestered in the Earth for tens and even hundreds of millions of years. In addition to spurring global warming, the burning of gasoline and diesel fuels releases a host of pollutants and heavy metals that affect local and regional air quality. Transport-related air pollution leads to reduced visibility, damage to vegetation and buildings, and increased incidence of human illness and premature death (including tens of thousands of premature deaths annually in the United States alone).[20] Road transport is also a growing contributor to air pollution in many developing country cities, particularly where diesel remains the predominant fuel.[21]

Table 13–1 summarizes some of the main environmental and health impacts associated with petroleum’s primary combustion products, including CO_2, CO, unburned hydrocarbons (particularly benzene), NO_x, SO_x, particulates and, in some countries, lead.[22]

Table 13–1. Environmental and Health Impacts of Emissions from Petroleum Combustion

Combustion Product	Impacts
CO_2	Contributes to global warming and climate change.
CO	Results from incomplete burning. In the atmosphere, CO reacts with oxygen to form ozone (0_3), a highly reactive molecule that damages plant leaves and human and animal lungs. When breathed, CO

	prevents oxygen molecules from attaching to blood hemoglobin. It is hazardous to people with cardiac, respiratory, and vascular disease.
Benzene	The smallest aromatic hydrocarbon and a highly toxic carcinogen. Larger aromatic and olefin hydrocarbon chains are precursors for ozone and particulates.
NO and NO_2	Ozone precursors. They also react with atmospheric water to form nitrogen acids, creating acid rain that, among other things, corrodes buildings and plants, and depletes soil nutrients.
SO_2 and SO_3	Acid-rain precursors, they also tend to form sulfate-based particulate matter. SO_2 exposure can cause respiratory disease, breathing difficulties, and premature death. Sulfur can render vehicle catalytic converters useless.
Particulates	Formed from SO_x, NO_x, and hydrocarbons. Contribute to ozone formation and affect visibility. Once inhaled, they can pass deeply into the lungs and contribute to asthma, cancer, and heart disease. The primary difference between gasoline and diesel combustion is that diesel emits more particulates. Particulate matter contributes to more than 15,000 premature deaths in the United States each year.
Lead	Has been phased out of gasoline in most countries, but is still used as an octane enhancer in some countries, particularly in Africa. As a neurotoxin, it can impair the nervous system, stunt growth, and cause learning disabilities. Lead poisoning is more common among children where gasoline has high lead content.

Sources: See Endnote 22 for this chapter.

13.3 Biofuel Impacts: Refining

Like petroleum fuels, biofuels can have environmental impacts at all stages of their production and use. Relative to fossil fuels, however, the impacts resulting from refining, transporting, and using biofuels are generally significantly smaller. Moreover, there are ways to improve the resource efficiency and impacts of these activities.

13.3.1 Water Use

Processing biofuel feedstock into fuel can use large quantities of water. The primary uses of water for biodiesel refining are to wash plants and seeds for processing and then to remove the soap and catalyst from the oils before the final product is shipped out. Sheehan et al. (1998) estimate that a typical U.S. soybean crushing system requires just over 19 kilograms of water per tonne of oil produced.[23] For each tonne of soybeans that go into the refining process, 170 kilograms come out as crude, degummed soybean oil, 760 kg are soy meal, and the remaining 70 kilograms include air, solid (non-hazardous remains of beans) and liquid waste.[24] The primary contaminant in the wastewater is soybean oil.[25]

Production of ethanol in particular requires a tremendous amount of water—for processing and for evaporative cooling—to keep fermentation temperatures at the required level (32–33ºC).[26]

But some feedstock are more water intensive than others: each tonne of sugar cane in Brazil, for example, requires as much as 3,900 liters for processing.[27] The concentration of slurry fed into the hydrolysis process must be similar for all feedstock, so more process water is needed for less-starchy grains than for starch-rich grains such as corn.[28]

Ethanol processing also results in large volumes of nutrient-rich waste water that, if not cleaned and recycled, can speed eutrophication of local rivers and streams by affecting the water's dissolved oxygen content.[29] In addition, sugar mills must be flushed every year, putting huge amounts of organic matter into local waterways.[30] In Brazil, one liter of ethanol produces about 10–15 liters of stillage (vinasse), which is very hot and corrosive, with a low pH and high mineral content.[31] In 1979, the volume of vinasse produced in Brazil exceeded the amount of sewage waste produced by the nation's entire population.[32] For years, the costs of pumping and storage were so high in the mountainous regions of the country's northeast that vinasse was released directly into rivers, causing enormous fish kills at every harvest.[33]

Today, however, wastewaters and vinasse are recycled and used for irrigation and fertilization of Brazil's sugar cane crops, with varying quantities of vinasse used under different conditions as regulated by law.[34] However, some experts caution that vinasse cannot be used where water tables are higher, such as in India.[35] Also, if used excessively, like nitrogen fertilizer vinasse can cause eutrophication of surface waters due to the increased nutrient load.[36] Filter cake, another waste stream from ethanol processing, is also recycled as a fertilizer. As a result, Brazil has been able to significantly reduce its use of petroleum fertilizers, saving money while creating value from waste products.[37]

Water pollution is not exclusively a Brazilian problem. In the U.S. state of Iowa (where a large share of U.S. ethanol is produced), ethanol processing plants have sent syrup, bad batches of ethanol, and sewage (containing chloride, copper, and other wastes) into nearby streams. At times, the pollution dumped from such facilities has been strong enough to kill fish. While there are laws to prevent this practice in the United States, they are not always clear and thus are open to interpretation, and some plants are violating them. As a result, efforts are under way to develop new water quality standards to reduce pollution.[38]

Fortunately, the problem of nutrient loading in streams and the associated problem of increased biological oxygen demand can be resolved by installing various treatment systems for these organic wastes, including anaerobic digester systems.[39] And, at least in the United States, standard wastewater treatment technologies can eliminate virtually all pollutants and about 95 percent of the water can be reused, substantially reducing the amount of freshwater required for processing; the remainder is retreated and then released. Methane, which can be used as a fuel, is captured in the process, creating an economic incentive to treat the water; still, regulations are necessary to ensure the proper treatment of wastewater.[40] However, as the scale of production increases, there is some concern that, even in the United States, some small municipal systems will be unable to deal with the large quantities of wastewater discharged from high-capacity plants (for example, those producing 110,000–150,000 cubic meters of ethanol annually).[41]

The other production-related pollutant that affects water is waste heat, which is needed for processing and is generated by the fermentation process. Hot water released into local streams or rivers can kill fish and alter ecosystems. Alternatives exist, however, for removing excess heat through evaporation (wet cooling system), or the use of air in dry cooling systems, or the hot water can be used for heat and cogeneration.[42]

Other waste products that result from the refining process include biosolids from wastewater treatment and the ash content of biomass. But it is possible that uses will be found for these wastes, as has been the case with the petroleum industry.[43] As mentioned earlier, ash is already used in some instances to return nutrients to the soil.

13.3.2 Air Pollution

Among the pollutants that biorefineries emit into the air are NO_x, SO_x, VOCs, CO, and particulate matter. Emissions from corn-ethanol plants, for example, include SO_x, NO_x, CO, mercury, particulates, and CO_2.[44] Corn-ethanol plants in Iowa have polluted both water and air, emitting cancer-causing chemicals such as formaldehyde and toluene.[45]

Biodiesel production requires methane, which has the same environmental costs as those associated with petroleum production. Otherwise, direct emissions from biodiesel processing plants include air, steam, and hexane, which is used to extract oil from plants and seeds. Hexane is an air pollutant, and though as much as possible is recovered and recycled, some is emitted into the air as well. Sheehan et al. (1998) estimate that the average U.S. soybean crushing system releases just over 10 kilograms of hexane per tonne of oil produced. Alternatives have been found such that hexane is no longer needed, but these options are more costly.[46] In addition, where renewable resources are not used to produce process energy, pollutants associated with the use of natural gas and generation of steam and electricity are released into the air. An estimated 3.6 kilowatt-hours of electricity are required per tonne of soybeans entering a soy biodiesel plant.[47] On the other hand, Fischer-Tropsch biodiesel is gasification-based and therefore has minimal local air pollution problems.[48]

As plant size increases, concerns about pollution—including air emissions, odors released during drying of distillers grains in corn-ethanol plants, and wastewater discharges—have risen as well.[49] However, with appropriate regulation and pollution-control technologies, emissions associated with biofuels refining can be minimized significantly.[50*] For example, NO_x emissions from boilers can be reduced by installing new NO_x burner systems.[51] VOC emissions, which result primarily from the blending of ethanol with gasoline, can be reduced by mixing the fuels at locations where pollutants can be collected and treated.[52] In some cases, new and larger plants are incorporating such emissions control systems and finding alternative options that enable them to reduce such emissions.[53]

In addition, much of the air pollution associated with biofuels refining results from the burning of fossil fuels for process heat and power—which in the United States, Germany, China, and many other countries is mainly coal. Thus, emissions can be reduced through traditional power plant control technology or the use of renewably generated power.[54]

In Brazil today, mills and distilleries meet most if not all of their own energy needs with bagasse (a byproduct of sugarcane crushing), which can generate thermal, mechanical, and electrical energy.[†] Some plants even sell surplus electricity into the grid.[55] Elsewhere, agricultural and forestry residues can be used to produce required power and heat; however, it is important to ensure that enough residues remain to maintain soil organic matter and nutrient levels.[56]

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[*] In early 2006, the U.S. Environmental Protection Agency was considering easing air emissions standards for ethanol plants to boost the nation's ethanol supplies. See Tom Doggett, "EPA Seeks to Ease US Ethanol Plant Pollution Rules," *Reuters*, 3 March 2006.
[†] However, that burning of bagasse also emits NO_x, CO, and particulates.

13.4 Biofuel Transport and Storage

13.4.1 Water Pollution

Pure ethanol and biodiesel fuels offer significant environmental benefits compared to petroleum fuels, making them highly suitable for marine or farm uses, among others. They result in dramatically reduced emissions of VOCs and are less toxic to handle than petroleum fuels.[57] One other significant advantage relates specifically to water: both ethanol and biodiesel are biodegradable and break down readily, reducing their potential impact on soil and water.[58]

Biodiesel is far more water-soluble than petroleum diesel, enabling marine animals to survive in far higher concentrations of it than petroleum if fuel spills occur (due to lower risk of suffocation).[59] Such benefits are helping to drive biofuel-promotion policies in China, where vehicle spills have polluted water bodies and gasoline and diesel leakage from pipelines has polluted groundwater—affecting biodiversity, drinking water, and soil resources.[60]

At least one study has shown that biodiesel made with rapeseed oil can biodegrade in half the time required for petroleum diesel. Biodiesel also speeds the rate at which biodiesel-petroleum blends can biodegrade, which is not the case with ethanol.[61] There is evidence that ethanol's rapid breakdown depletes the oxygen available in water and soil, actually slowing the breakdown of gasoline. This can increase gasoline's impact on the environment in two ways. First, the harmful chemicals in gasoline persist longer in the environment than they otherwise would; benzene, in particular, can last 10–150 percent longer when gasoline is blended with ethanol. Second, because gasoline breaks down more slowly, it can travel farther (up to 2.5 times) in the marine environment, affecting a greater area.[62]

Additionally, if ethanol is spilled, it can remobilize gasoline in previously contaminated soils, intensifying the impacts of the initial spill. As up to 85 percent of such spills occur at gasoline terminals, this is where such a problem is most likely to happen.[63] The transition to high levels of ethanol needs to be planned with such impacts in mind, and should include regulations for the handling of fuels.[*]

13.4.2 Air Pollution

Most biomass is carried to processing plants by truck, and most biofuels are transported by truck as well, though some travel by train or, in Brazil, via pipelines. The environmental impacts associated with transport include the air emissions and other pollutants associated with the life cycle of the fuel used—in most cases, petroleum diesel. As demand for biofuels increases and as consumption exceeds production in some countries, it is likely that a rising amount of feedstock and biofuel will be transported by ship. While shipping is a relatively energy efficient means of transport, it is also a major source of pollution, due primarily to a lack of regulations governing maritime emissions. Pollutants include NO_x, SO_2, CO_2, particulate matter, and a number of highly toxic substances such as formaldehyde and polyaromatic hydrocarbons.[64] Emissions from diesel marine engines represent an ever-increasing share of air pollution, and

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[*] It is important to note that many of toxic chemicals in gasoline are actually additives; if these were not in the gasoline, spill-related problems would be reduced.

most of these pollutants are released near coastlines, where they can easily be transported over land.[65]

The other potential concern associated with biofuels transport is the possibility for spills and evaporation. Biofuels can leak at the production facility, spill while being transported, and leak from above- or below-ground tanks. They can also evaporate during fueling and storage and from a vehicle's fueling system.

In general, "neat" biofuels are distinctly less toxic than spills of petroleum fuels. For biodiesel, evaporative emissions are not a particular concern, since biodiesel fuel does not have a higher vapor pressure. Neat ethanol has a low Reid vapor pressure (RVP), and when stored as a pure fuel (or even as an E-85 blend), it has a lower vapor pressure than gasoline, and thus will have fewer evaporative emissions.[66]

The primary concern regarding emissions from biofuel transport has to do with lower-level blends of ethanol in gasoline, which tend to raise the vapor pressure of the base gasoline to which ethanol is added. When ethanol is blended up to about 40 percent with gasoline, the two fuels combined have higher evaporative emissions than either does on its own. The fuels are mixed via splash blending at the petroleum supply "rack," so there is a potential for increased evaporative emissions from these lower-level blends at the point in the distribution chain and "downstream"—mainly during vehicle refueling and on-board vehicles. These evaporative emissions from a vehicle's fueling system can increase ozone pollution.

Adding the first few percent of ethanol generally causes the biggest increase in volatility, so increasing the blend level to 2 percent, 5 percent, or even 10 percent will have similar results.[67][68] Evaporative emissions peak at blend levels between 5–10 percent, and then start to decline. Once ethanol's share exceeds 40 percent, evaporative VOC emissions from the blend are lower than those from gasoline alone.[69]

Most IEA (International Energy Agency) countries have emissions standards requiring that VOC emissions, and thus RVP, be controlled.[70] Emissions resulting from higher vapor pressure can be controlled by requiring refiners to use base gasoline stock with a lower vapor pressure when blending it with ethanol, although this increases costs and reduces production levels. The U.S. state of California and U.S. federal reformulated gasoline programs have set caps on vapor pressure that take effect during high ozone seasons in areas that do not meet ambient air quality standards for ozone.[71] As a result, the addition of ethanol does not increase the vapor pressure of the gasoline available during summer months.[72] Emissions from permeation are more difficult to control in the on-road fleet, although experts believe that most can be controlled in new vehicles that must meet stricter evaporative emission control standards (such as California LEV 2 and U.S. Federal Tier II), with higher-quality tubes, hoses, and other connectors.[73] (See Chapter 15 for more on vehicle and engine technologies.)

13.5 Biofuel Combustion

The level of tailpipe emissions that results from the burning of ethanol and biodiesel depends on the fuel (e.g., feedstock and blends), vehicle technology, vehicle tuning, and driving cycle.[74] Most studies agree that using biofuels can significantly reduce most pollutants compared to petroleum fuels, including reductions in controlled pollutants as well as toxic emissions.[75] NO_x

emissions have been found to increase slightly as blend levels rise, though the level of emissions differs from study to study.

13.5.1 Ethanol

Ethanol contains no sulfur, olefins, benzene, or other aromatics[*], all of which are components of gasoline that can affect air quality and threaten human health.[76] Benzene is a carcinogen, while olefins and some aromatics are precursors to ground-level ozone (smog).[77] Ethanol-gasoline blends also reduce toxic emissions of 1,3-butadiene, toluene, and xylene. While few studies have looked at the impacts on pollution levels from high blends, it appears that impacts are similar to those from low blends.[78]

With ethanol fuel combustion, emissions of the toxic air pollutants acetaldehyde, formaldehyde, and peroxyacetyl nitrate (PAN) increase relative to straight gasoline.[79] Most is emitted as acetaldehyde, a less-reactive and less-toxic pollutant than formaldehyde.[80] Neither pollutant is present in the fuel; they are created as byproducts of incomplete combustion.[81] PAN, an eye-irritant that is harmful to plants, is also formed as a byproduct.[82] A U.S. auto-oil industry study determined that combustion of E85 resulted in a slight increase in hydrocarbon emissions relative to California reformulated gasoline. It also found that toxic emissions rose as much as 2–3 fold compared to conventional gasoline, due mainly to an increase in aldehyde emissions.[83]

There is concern that aldehydes might be carcinogenic, but the pollutants that are reduced by blending with ethanol (including benzene, 1,3-butadiene, toluene, and xylene) are considered more dangerous to human health.[84] A study done in California determined that acetaldehyde and PAN concentrations increase only slightly with ethanol blends, and a Canadian study concluded that the risks of increased aldehyde pollutants are negligible.[85] Because of the reactivity of aldehydes, emissions can generally be managed with emissions controls.[86] For example, three-way catalysts can efficiently minimize aldehyde emissions.[87]

Ethanol-blended gasoline increases fuel oxygen content, making hydrocarbons in the fuel burn more completely in older vehicles in particular, thus reducing emissions of CO and hydrocarbons. Note that oxygen sensors in newer vehicles control engine combustion, reducing the benefit that ethanol can provide in reducing CO and hydrocarbon emissions.[88] Ethanol used as an additive or oxygenate (a 10 percent blend, for example) has been found to achieve CO reductions of 25 percent or more in older vehicles.[89] In fact, one of the goals driving the use of ethanol in the United States during the 1990s was to reduce hydrocarbon and CO emissions, particularly in winter when emissions of these pollutants tend to be higher.[90] Ethanol in higher blends will positively affect the efficiency of catalytic converters because of the dilution of sulfur.[91] Ethanol can also be used to make ETBE (ethyl tertiary butyl ether), which is less volatile than ethanol and widely used in the European Union.[92][†]

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[*] Note, however, that ethanol sold at fueling stations could contain some of these in low amounts because, by law, poisons must be added to it. They are usually gasoline components, and whatever is cheapest.

[†] Note, however, that since ETBE has toxicity levels similar to the fuel additive methyl tertiary butyl ether (MTBE), concern in the United States regarding fuel/MTBE leaks from underground storage tanks is expected to be a major barrier to acceptance of ETBE in that country. (See Chapter 2 for more information.)

As a result of its national ethanol program, Proálcool, Brazil was one of the first countries in the world to eliminate lead entirely from its gasoline. According to the São Paulo State Environment Agency (CETESB), ambient lead concentrations in the São Paulo metropolitan region declined from 1.4 grams per cubic meter in 1978 to less than 0.1 g/m^3 in 1991.[93] Most other countries, however, have been able to eliminate lead through other means, including a reduction in unnecessarily high octane grades and the development of cheaper refining alternatives (e.g., reforming, isomerization).[94]

Ethanol use has resulted in significant reductions in other air pollutants as well. Emissions of toxic hydrocarbons such as benzene have declined in Brazil, in addition to emissions of sulfur and CO: for example, Brazil's transport-related CO emissions declined from more than 50 grams per kilometer in 1980 to less than 1 gram/km in 2000, due to ethanol use. CETESB estimates that urban air pollution in Brazil could be reduced an additional 20–40 percent if the entire vehicle fleet were fueled by alcohol.[95] In 1998, Denver, Colorado, became the first U.S. city to require blending of gasoline with ethanol; it is used in winter to improve fuel combustion and to reduce CO emissions. As a result, it is estimated that CO levels have declined by 50 percent.[96]

As noted above, there is some evidence that emissions reductions associated with using ethanol blends, as compared to straight gasoline, are not as significant in the cleanest vehicles available today. Durbin et al. (2006) tested vehicles that qualified as low-emission and ultra-low emission in California, and found that emissions of non-methane hydrocarbons increased as engine temperatures rose and that benzene emissions increased with higher concentrations of ethanol, while fuel efficiency declined. However, CO emissions decreased somewhat with ethanol use.[97] Some of the findings were inconsistent with those of other studies, highlighting the need for further research.[98]

As discussed earlier, ethanol used as an oxygenate can reduce emissions of several pollutants, particularly in older vehicles. However, the use of oxygenates, such as ethanol (and biodiesel), to alter the fuel-to-oxygen ratio will not necessarily have a positive effect on emissions if a vehicle's air-to-fuel ratio is set low or if too much ethanol is added to gasoline in a vehicle with a fixed air-to-fuel ratio. If that is the case, oxygenates can increase NO_x emissions and cause "lean misfire," increasing hydrocarbon emissions.[99] In fact, Tyson et al. (1993) argue that ethanol has no emission-related advantages over reformulated gasoline other than the reduction of CO_2.[100]

Ethanol blended with diesel can provide substantial air quality benefits. Blends of 10–15 percent ethanol (combined with a performance additive) result in significantly lower emissions compared with pure diesel fuel: tailpipe emissions of PM, CO, and NO_x decline. For high blends, the results are mixed. Some studies have found higher average CO and hydrocarbon emissions, and others have seen reductions in these pollutants. However, all studies to date have seen significant decreases in both PM and NO_x.[101]

Flexible-fuel vehicles (FFVs)—which can take virtually any ethanol-gasoline blend up to 85 percent in the United States, and up to 100 percent in Brazil—are widely used in Brazil and are becoming increasingly available in the United States. However, tests to date have found that the use of FFVs result in higher air emissions than new gasoline vehicles.[102] Because it is not possible to tune the combustion controls of a vehicle so that it is optimized for all conditions, controls are compromised somewhat to allow for different mixes.[103] It is possible that vehicles dedicated for specific blends, and operated on those blend levels, would achieve lower emissions than conventional vehicles.[104]

13.5.2 Biodiesel

Biodiesel—whether pure or blended—results in lower emissions of most pollutants relative to diesel, including significantly lower emissions of particulates, sulfur, hydrocarbons, CO, and toxins.[105] Emissions vary with engine design, condition of vehicle, and quality of fuel. In biodiesel-diesel blends, potential reductions of most pollutants increase almost linearly as the share of biodiesel increases, with the exception of NO_x emissions.[106]

In one of the most comprehensive analyses to date, a U.S. Environmental Protection Agency (EPA) study of biodiesel determined that the impacts on emissions vary depending on type (feedstock) of biodiesel and the type of petroleum diesel it is mixed with. Overall, animal-based biodiesel did better in the study than plant-based biodiesel with regard to reducing emissions of NO_x, CO, and particulates. On average, the EPA determined that B20 (made with soybeans) increased NO_x emissions by 2 percent, and reduced emissions of particulates by 10 percent, CO by 11 percent, and hydrocarbons by 21 percent, while also reducing toxic emissions. Biodiesel made from animal fats increased NO_x emissions the least, followed by rapeseed biodiesel, and then soybean-based biodiesel; the same relationship held true to CO reductions as well. Reductions in particulate emissions were also greatest for animal-based biodiesel.[107]

Tests carried out by the EPA showed that, when compared with conventional diesel, pure biodiesel (produced with soybean oil) resulted in average reductions of particulate matter by 40 percent, carbon monoxide by 44 percent, unburned hydrocarbons by 68 percent, polycyclic aromatic hydrocarbons (PAHs) by 80 percent, carcinogenic nitrated PAHs by 90 percent, and sulfates by 100 percent.[108]

In 2000, biodiesel became the first alternative fuel to successfully complete testing for Tier 1 and Tier 2 health effects under the U.S. Clean Air Act. Tests determined that, with the exception of minor damage to lung tissue at high levels of exposure, animals observed in the study suffered no biologically significant short-term effects associated with biodiesel.[109]

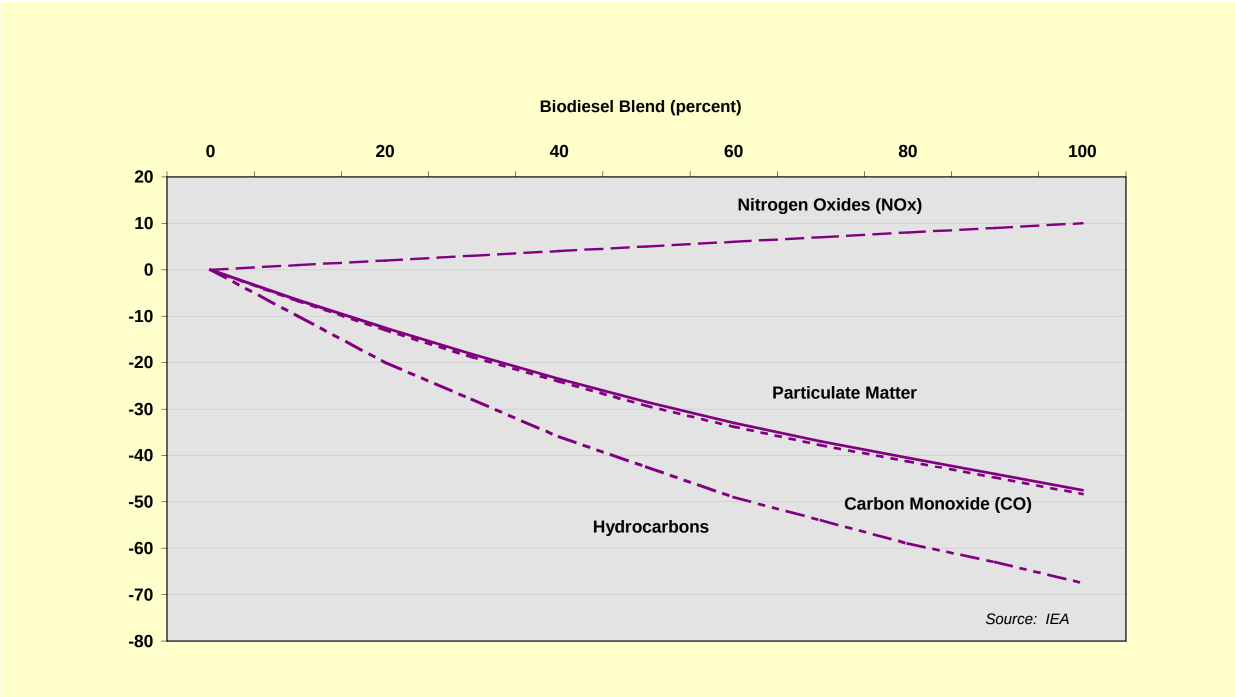
A 1999 Swedish study by Pedersen et al. found that biodiesel (RME) led to an up to 10-fold increase in emissions of benzene and ozone precursors compared with Swedish low sulfur diesel fuel, called MK1.[110] However, this study was done using a very small reactor; many U.S. and European researchers were skeptical about transferring results from this study to the real world for combustion in a diesel engine. Since then, other studies have produced different results. For example, Krahl et al. (2001) compared 100 percent RME to MK1, fossil diesel fuel, and another low sulfur diesel fuel (with high aromatic compounds content and flatter boiling characteristics, known as DF05), using a modern DaimlerChrysler diesel engine such as those generally installed in light-duty transport vehicles. They concluded that RME led to significant reductions in CO, HC, aromatic hydrocarbons (including benzene), and aldehydes and ketones (which contribute to formation of summer smog) compared with the other fuels.[111]

However, Krahl et al. (2001) did determine that RME resulted in more emissions of particles in the 10–40 nanometer diameter range, and fewer in the larger diameter range relative to fossil diesel (ultra fine particles are considered to be more toxicologically relevant than larger particles), whereas MK1 led to reduction over the entire measuring range, and DF05 led to an increase across whole range compared with fossil diesel fuel. At the same time, RME resulted in a considerable decrease in total particle mass relative to the other fuels tested, and produced almost no soot. And the mutagenic effects of particle extracts from RME were the lowest, indicating a reduced health risk from cancer associated with the use of RME relative to fossil diesel and the other fuels tested.[112]

13.5.3 Impacts on NO_x Emissions

Most studies conclude that ethanol and biodiesel emit higher amounts of nitrogen oxide (NO_x) than do conventional fuels, even as other emissions decline.[113] (See Figure 13–1.) There are exceptions, however. When ethanol is blended with diesel, NO_x emissions decline relative to pure diesel fuel; and some tropical oils are saturated enough—and thus have a high enough cetane value—that they increase NO_x less, and in the case of highly saturated oils such as coconut, actually decrease NO_x relative to diesel.[114] NO_x are a precursor to ground level ozone (smog). In addition, NO_x emissions increase acid rain and are precursors to fine particulate emissions; associated health impacts include lung tissue damage, reduction in lung function, and premature death.[115]

Figure 13–1. Tailpipe Emissions from Varying Biodiesel Blends Relative to Emissions from 100 Percent Petroleum Diesel Fuel



The level of NO_x emissions found varies significantly from study to study. Some cities, particularly in the U.S. state of California, have complained that ethanol has increased local problems with NO_x and ozone.[116] California is using ethanol as an oxygenate to meet requirements under the U.S. Clean Air Act, because concern about water contamination led the state to ban MTBE. More recently, concerns about evaporative VOC emissions and combustion emissions of NO_x led California to sue the U.S. EPA twice for a waiver; both times the waiver was denied.[117] But both the EPA and California Air Resources Board agreed during the process that ethanol increases NO_x slightly in the on-road fleet.[118]

Fulton et al. (2004), on the other hand, report that the impacts of biofuels on NO_x emissions levels are relatively minor and can actually be higher or lower than conventional fuels, depending on conditions. In fact, there is evidence that NO_x levels from low ethanol blends range from a 10 percent decrease to a 5 percent increase relative to pure gasoline emissions.[119]

Studies by the U.S. National Renewable Energy Laboratory (NREL) show inconsistent results with regard to biodiesel and NO_x, depending on whether the vehicle is driven on the road or in the laboratory. According to McCormick (2005), they have seen "… NO_x reductions for testing of vehicles (chassis dyno) and NO_x increases for testing of engines (engine dyno)." The former, which involves driving an entire car on rollers rather than testing emissions directly from an engine removed from the vehicle, is considered more realistic than the latter.[120]

NREL studies of in-use diesel buses have found a statistically significant reduction in NO_x emissions with biodiesel.[121] A U.S. auto-oil industry six-year collaborative study examined the impact of E85 on tailpipe emissions and found that NO_x emissions were reduced by up to 50 percent relative to conventional gasoline.[122] But India's Central Pollution Control Board has determined that burning biodiesel in a conventional diesel engine increases NO_x emissions by about 13 percent.[123]

Fortunately, newer vehicles designed to meet strict air standards, such as those in California, have very efficient catalyst systems that can reduce VOC, NO_x and CO emissions from ethanol-gasoline blends to very low levels.[124] With biodiesel, NO_x increases can be minimized by optimizing the vehicle engine for the specific blend that will be used.[125] Emissions can also be reduced with additives that enhance the cetane value, or by using biodiesel made from feedstock with more saturated fats (e.g., tallow is better than canola, which is better than soy).[126]

It is also possible to control diesel exhaust using catalysts and particulate filters. High efficiency diesel particulate filters (DPF) remove particulate matter (PM) by filtering engine exhaust; such systems can reduce PM emissions by 80 percent or more.[127] However, because of concerns about increased oil film dilution during post-injections, German car manufacturers do not accept neat biodiesel in DPF-equipped vehicles.[128] There is also concern that the extra injection used to increase emission temperatures for regeneration of the particulate trip results in a dilution of engine oil when RME is used as a fuel, and this dilution can increase engine wear.[129] Rust particle filters, which are available in many new diesel automobiles and significantly reduce emissions of fine particulates, cannot operate with biodiesel.[130] According to some sources, biodiesel does not meet European air emissions standards that went into effect in January 2006[131], although the Association of the German Biofuel Industry notes that biodiesel can meet updated European standards for trucks and commercial vehicles.[132]

Several groups are in the process of developing additives to address the issue of NO_x emissions associated with biodiesel blends, including NREL, the U.S. National Biodiesel Board, the U.S. Department of Agriculture, and World Energy Alternatives.[133]

13.5.4 Advanced Technologies

In general, the air quality benefits of biofuels are greater in developing countries, where vehicle emissions standards are non-existent or less stringent and where older, more polluting cars are more common.[134] For example, the use of ethanol can effectively reduce emissions of CO and hydrocarbons in old-technology vehicles today.[135] Less understood, however, are the impacts that biodiesel might have on exhaust emissions from vehicles that are under-powered, over-fueled, over-loaded, and not well-maintained—vehicles that are also most prevalent in the world's developing nations.[136]

Advances in pollution-control technologies for petroleum-fueled vehicles will reduce, if not eliminate, the relative benefits of biofuels. Greene et al. (2004) note that the main benefit of biofuels in such advanced vehicles may be to make it easier to comply with emissions standards in the future, thus reducing the cost of emissions-control technologies.[137]

At the same time, new technologies are on the horizon. For example, Volkswagen and DaimlerChrysler have invested in biomass-to-liquid (BTL) technologies that convert lignocellulosic fibers into synthetic biodiesel. This process enables them to produce a cleaner burning biofuel. In the future, they hope to optimize fuels and vehicle engines in parallel.

13.6 Conclusion

The refining, transport, and combustion of biofuels have environmental costs, particularly on local water and air quality, and these impacts could rise considerably as biofuel production increases to meet rapidly rising global demand. At the same time, more-sustainable practices and new technologies offer the potential for environmental improvements.

Increasing efficiencies in water and energy use at refineries can help to reduce both air and water pollution. The UK-based biodiesel producer D1 Oils now recycles both water and methanol used in its refineries, and uses biodiesel to run its facilities.[138] Standards and regulations are also needed to minimize pollutants. In addition, encouraging smaller scale, distributed facilities will make it easier for communities to manage wastes, while possibly relying on local and more varied feedstock for biofuels production and thereby benefiting local economies and farmers.

The combustion of biofuels—whether blended with conventional fuels, or pure—generally results in far lower emissions of CO, hydrocarbons, SO_2, and particulate matter (and in some instances lead) than does the combustion of petroleum fuels. Thus, the use of biofuels, particularly in older vehicles, can significantly reduce local and regional air pollution, acid deposition, and associated health problems such as asthma, heart and lung disease, and cancer.[139]

However, the air quality benefits of biofuels relative to petroleum fuels will diminish as fuel standards and vehicle technologies continue to improve in the industrialized and developing worlds. Even today, the newest vehicles available for purchase largely eliminate the release of air pollutants (aside from CO_2).[140] At the same time, concerns about higher levels of NO_x and VOC emissions from biofuels will likely diminish with improvements in vehicles, changes in fuel blends, and additives. A combination of next-generation drive chains (based on internal combustion engines) and next-generation biofuels can make a major contribution to reducing air pollution in the transport sector.

In the developing world, ethanol should be used to replace lead, benzene, and other harmful additives required for older cars. And because high blends or pure biofuels pose minimal air emissions problems and are less harmful to water bodies than petroleum fuels, for all countries it is important to transition to these high blends as rapidly as possible, particularly for road transport in highly polluted urban areas and for water transport wherever feasible.

PART V. MARKET INTRODUCTION AND TECHNOLOGY STRATEGIES

Chapter 14. Infrastructure Requirements

14.1 Introduction

A dramatic expansion in biofuel production capacity worldwide will require substantial new investments in biofuels and related infrastructure. Existing experience with current feedstock and conversion technologies can provide useful insight into the infrastructure that will be needed for next-generation cellulose-based biofuel production in the coming years. The experience of the few countries where major biofuel developments have been under way for more than a decade will be particularly useful to those countries that are just beginning their own biofuel initiatives.

This chapter discusses the basic infrastructure considerations that need to be addressed for either of the two basic feedstock options, including: degree of concentration of production (distributed vs. centralized); transportation of feedstocks and of finished biofuel products (via truck, rail, barge, ship, and possibly pipeline); investments in new conversion facilities; investments in biofuel storage capacity; and investments in vehicle refueling facilities. The chapter focuses primarily on the experiences in ethanol infrastructure development in Brazil and the United States, and on biodiesel infrastructure development in Germany. The emphasis is mainly on larger-scale biofuel production facilities, which are likely to dominate future production.

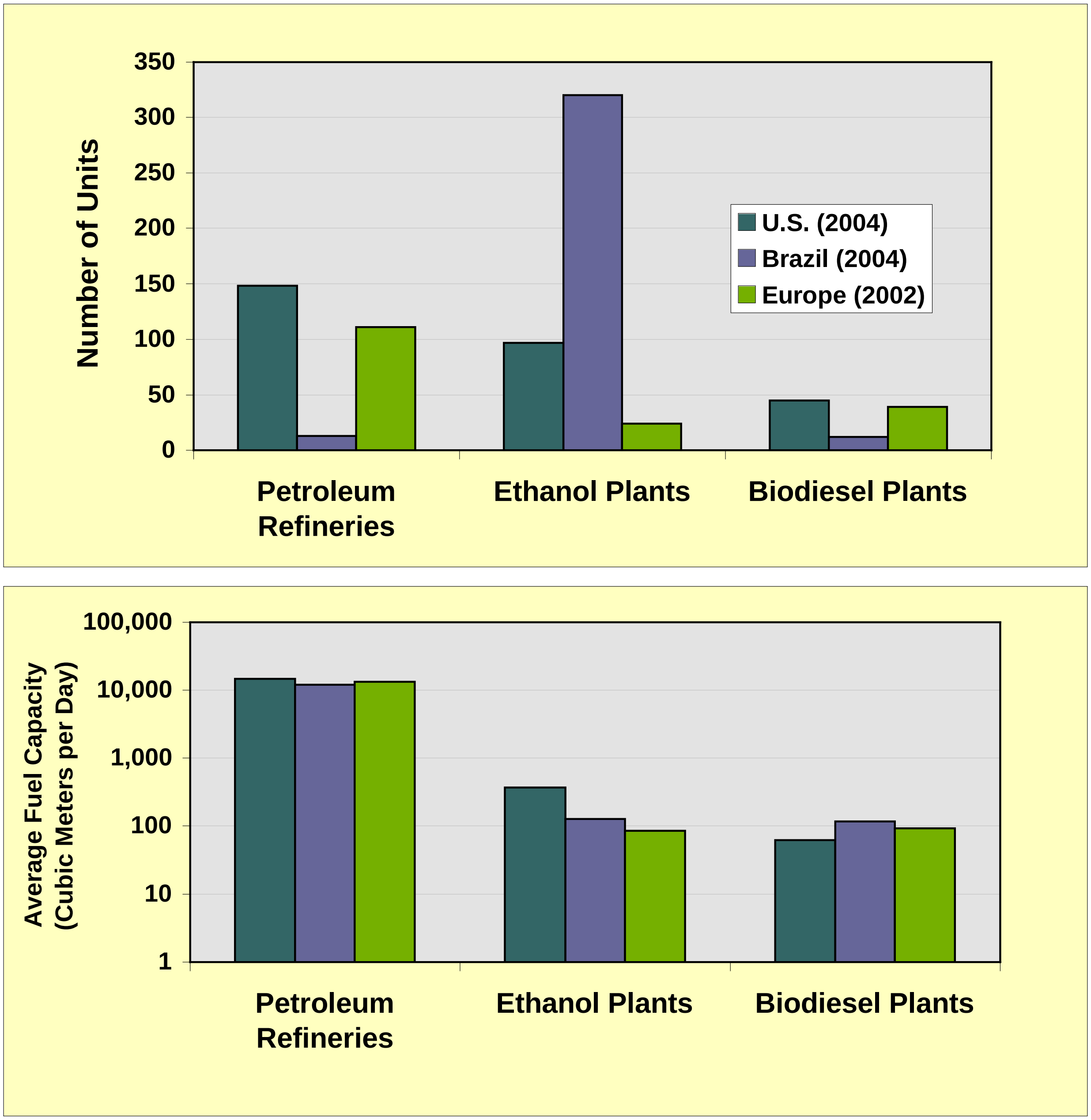
14.2 Centralized vs. Distributed Production

Compared to petroleum refining, which is developed at a very large scale, biofuel production is lower volume and more decentralized. In the case of biodiesel in particular, where a wide range of plant and animal feedstock can be used, there has been a tendency for rather dispersed production facilities. Producers have the ability to extract raw vegetable oil at one site and send the oil to a different location for processing.

Ethanol fuel production, which is ten times greater than current biodiesel production, has tended to be more geographically concentrated, but is broadly distributed among different facilities within a specific production region. In the United States, it is predominantly concentrated in Midwestern states that have abundant corn supplies, such as Iowa, Illinois, Minnesota, Nebraska, and South Dakota. In Brazil, sugar cane and ethanol production is concentrated in the center-south region, mainly in the state of São Paulo.

Compared to the oil industry, however, the ethanol production capacity in both the United States and Brazil is significantly more decentralized. Petroleum refineries that produce gasoline and diesel fuel are considerably larger than the facilities that produce ethanol and biodiesel. Consequently, in the world’s largest biofuel-producing regions, the average capacity of individual petroleum refineries is two orders of magnitude higher than the plants producing biofuels.[1] (See Figure 14–1.)

Figure 14–1. Number of Plants and Their Average Fuel Production in the U.S., Brazil, and Europe



Despite the two countries' somewhat similar overall ethanol output, Brazil has three times more ethanol plants than the United States. Accordingly, the average capacity of plants in the U.S. is three times greater than the average capacity of those in Brazil. The largest plant in Brazil produces 328 million liters per year by crushing sugar cane, whereas in the U.S. the largest corn dry-milling ethanol plant produces 416 million liters per year.[2*] There are various reasons

[*] Nevertheless, it is important to note that most Brazilian sugar mills simultaneously produce sugar and ethanol, with each mill responsible for processing significant amounts of sugar cane. Thus, the largest ethanol-producing unit also uses sugar cane to produce 455,000 tonnes of sugar. Other reasons for the

for the differences in plant capacities. One key reason corn-to-ethanol plants can be larger is because substantial amounts of harvested corn can be stored for long periods of time, whereas sugar cane must be processed shortly after it is harvested (preferably within 24–48 hours to avoid deterioration of the sugar).

Despite being spatially concentrated in specific regions, ethanol production in Brazil and the United States is decentralized among different plants due to feedstock transportation costs and handling logistics, which place economic limits on the size of processing plants. Since unprocessed biomass tends to be bulky (particularly compared to petroleum fuels), transport and logistics play an important role in facility siting, and in overall biofuel economics.

14.3 Investment Requirements for Feedstock Transport and Processing

Transporting and processing feedstock requires investments in a wide range of areas, including transportation infrastructure and facility construction, as well as overall operating costs. Since biofuel production technology is not homogeneous, these costs depend on the region, technology used, feedstock type, labor costs, spatial distribution, existing transportation infrastructure, and other factors.

14.3.1 Investment in Feedstock Transport

Feedstock transportation cost is a function of the total distance and time required for hauling the biomass and the time for loading and unloading.[3]

In Brazil, the estimated costs of harvesting, loading, and transporting one tonne of sugar cane over 18 kilometers are €3.07, €0.50, and €2.01 ($3.71, $0.61, and $2.43) respectively, using medium-sized trucks; this corresponds to €0.11 ($0.13) per tonne for every kilometer of hauling distance.[4] This is actually a conservatively high transport cost estimate, since the sugar cane is often transported by special trucks with 2–3 trailers, rather than in single medium-sized trucks, which increases the fuel efficiency of cane transport and reduces the number of overall trips required.

In the United States, the current average costs of transporting wheat, corn, and soybeans by railroad are €26.95, €22.90, and €24.26 ($32.59, $27.70, and $29.33) per tonne, respectively.[5] The average *per kilometer* cost of corn transported by railroad in the U.S. is 1.58 eurocents (1.91 U.S. cents) per tonne. Another alternative for transporting corn is to use trucks. Table 14–1 shows the average grain transportation cost by truck for different U.S. regions and distances.[6]

A cost comparison of trucks versus railroad shows that the cost of transporting grains by truck is more than twice that of transporting grains by railroad. The advantage of trucks is that they can access more sites than a railroad or waterway.

Although production of biofuels from cellulosic feedstock such as crop and forestry residues, perennial grasses, organic wastes, and other sources of fiber is not yet commercially available,

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lower average ethanol capacity in Brazilian plants are related to significant transportation costs associated with sugar cane due to the lower alcohol yield per ton as compared with corn, and the limited duration of the operational season, which is around 180–210 days per year, as opposed to the ethanol from starch plants that operate year-round.

some data on these transport costs are available. A U.S. study of switchgrass transport estimated a hauling cost of €0.04 ($.05) per kilometer, assuming three trailers per truck and 11.5 dry tonnes per trailer.[7] The hauling time cost, which includes time-dependent variables such as the driver labor costs, as well as truck and trailer time costs including depreciation, interest, insurance, and fees, was estimated to be €3.65 ($4.42) an hour per dry tonne. Finally, the loading/unloading cost was estimated to be €2.74 ($3.32) per dry tonne.

Table 14–1. Average Grain Transportation Cost by Truck in the United States

Region	Transportation Cost (Euro cents/tonne per kilometer traveled)		
	≤40 km	≤160 km	≤320 km
National average	4.47	3.37	2.89
North Central region	3.99	3.14	2.80
Rocky Mountain	5.99	3.23	2.78
South Central	3.86	3.23	3.03
West	6.43	4.66	3.75

Note: Rates are based on trucks with a 36.3 tonne gross vehicle weight limit.
Source: See Endnote 6 for this chapter.

14.3.2 Investment in Biofuel Processing Plants

Ethanol Production

Table 14–2 compares the costs of producing ethanol from wheat and sugar beets in Germany with the costs of producing ethanol from corn in dry-milling facilities in the United States.[8] In general, ethanol production costs in Germany are somewhat lower for wheat than for sugar beets. There are also savings related to plant economies of scale, with overall capital costs lower for a 200 million liter plant than for a 50 million liter plant.

Table 14–2. Engineering Cost Estimates for Bioethanol Plants in Germany vs. the United States

Costs	Germany				United States
	50 million liter plant		200 million liter plant		53 million liter plant
	wheat	sugar beet	wheat	sugar beet	corn
	(Euros per liter)				
Feedstock cost	0.23	0.29	0.23	0.29	0.17
Co-product credit	-0.06	-0.06	-0.06	-0.06	-0.06
Net feedstock cost	0.17	0.23	0.17	0.23	0.12
Labor cost	0.03	0.03	0.01	0.01	0.02

Other operating and energy costs	0.17	0.15	0.17	0.14	0.09
Annualized net investment cost	0.08	0.08	0.05	0.05	0.03
Total cost	0.45	0.49	0.40	0.34	0.26
Total cost per liter gasoline-equivalent	0.67	0.73	0.59	0.64	0.40

Source: See Endnote 8 for this chapter.

In Brazil, the cost of an ethanol distillery with a 450,000-liter-per-day capacity is €28.12 million ($34 million), whereas the production of 1,100 tons of sugar cane per day (enough to feed an ethanol plant with this capacity using current technology) requires an investment of €14 million ($17 million).[9] Such investments correspond respectively to 26 and 12 euro cents (31 and 15 U.S. cents) per liter, assuming an 8 percent annual discount rate over 10 years.[*]

Biodiesel Production

Biodiesel investment costs in Brazil are estimated to range from €64 ($77) per 1,000 liters if methyl ester is used, to €83 ($100) per 1,000 liters if ethyl ester is used. In the United States, the investment required for biodiesel production is about €109 ($132) per 1,000 liters of production capacity. Feedstock costs correspond to an additional 70–85 percent of the final cost of biodiesel.[10] (See Table 14–3.)

Table 14–3. Cost Estimates for Investments in Biodiesel Production Capacity

	Facility cost/1000 liters	Total cost/1000 liters
large facility, Brazil (>1 million liters)	€ 64 ($77)	€ 427 ($531)
large facility, Brazil (ethyl esters)	€ 83 ($100)	€ 553 ($693)
large facility, U.S.	€ 109 ($132)	€ 450 ($563)
small facility, U.S.	€ 270 ($334)	€ 1100 ($1376)

Note: Assuming byproducts are sold and feedstock costs correspond to 85% of facility costs in Brazil and 75% in U.S.
Source: See Endnote 10 for this chapter.

A typical biodiesel plant is composed of two plants: the soybean processing plant and the transesterification plant. This separation of functions highlights a potential option of having soybean-processing facilities in completely different locations from the transesterification process. This separation could allow farmers to send unprocessed vegetable oil to a larger central transesterification facility, perhaps owned jointly by numerous farmers. It could also potentially be an approach used for international trade, where nations that produce vegetable oil

[*] In reality, the cost of money in Brazil is high and requires an annual discount rate of 20 percent in national currency, to attract investors. Thus, the values quoted should be considered low and would need to be adjusted depending on the discount criteria used by specific investors.

could send their product to countries that would then produce finished biodiesel to their own specifications.

In terms of the capital costs involved in developing smaller-scale biodiesel plants, for a plant with an installed soybean processing capacity of approximately 1,900 tons per year, paired with a transesterification plant with an installed capacity of 2.3 million liters per year, the costs would be about €414,000 ($500,000) and €223,000 ($270,000), respectively.[11] This corresponds to a capital cost of €0.27 ($0.33) per liter of annual biodiesel production capacity.[*]

Malaysia, the world's largest producer of crude palm oil, is planning to expand its production by up to 25 percent due to increasing demand for biodiesel. The Plantations Industries and Commodities Ministry aims to increase the yield of palm oil from current average levels of 4 tonnes per hectare (4,300 liters) up to 5 tonnes (5,400 liters) per hectare by 2010. The government is building three very large biodiesel plants, each with an annual capacity of 60,000 tonnes (65 million liters) and a cost of €26.4 million ($32 million).[12] There are different feedstocks involved, different labor rates, and investment criteria for the two cases.

Cellulose Conversion

The cost of a cellulosic biomass plant with a capacity of 542,000 liters per day is estimated to be €194 million ($234 million), which implies an annualized capital cost of €0.15 ($0.18) per liter (assuming an 8 percent annual discount rate over 10 years). This estimate is based on current technology and excludes operational costs, which on an annualized basis are similar to the facility’s capital cost.[13]

In general, cellulosic conversion plants will require greater capital investments than plants that convert sugar or starch, due to the extra steps needed to break down resistant cellulose plant fibers. The capital costs for gasification-based systems are expected to be somewhat higher than for enzymatic conversion systems; however, using wood in gasification systems should allow for larger plants that will benefit from economy-of-scale cost savings that should make gasification and enzymatic systems similarly competitive (since costs for both of these technologies are based on engineering estimates, there is clearly a need for real-world validation of costs before a definitive cost comparison can be made).

14.4 Investment Requirements for Biofuel Transport, Storage, and Delivery

The widespread production and use of biofuels depends on the existence of infrastructure for transport, storage, distribution, and delivery of the fuels. The investments and costs required for these steps depend on the type of fuel (gaseous vs. liquid), the type of vehicle using the fuel, and the existing transportation infrastructure.

14.4.1 Refueling Considerations for Gaseous vs. Liquid Biofuels

Since biofuels such as ethanol, ethyl tertiary butyl ether (ETBE), biodiesel, and synthetic diesel (from various biomass-to-liquids options) are liquid fuels, their similarity to petroleum fuels allows for much lower refueling station costs than for gaseous fuels such as hydrogen or compressed natural gas (CNG).

[*] This value does not take into account the value of the protein meal extracted from the soybeans.

It is possible to upgrade biogas from biomass digesters to natural gas quality for use in vehicles (similar to the CNG applications fairly common in many countries). However, the infrastructure costs for adding many new CNG refueling stations will be fairly high. The cost for fast-fill CNG refueling stations (i.e., ones that would allow for vehicle refueling times similar to gasoline or diesel refueling times) is on the order of €124,000 ($150,000) for a small station, €331,000 ($400,000) for a medium-sized station, and €830,000 ($1 million) for a large station.[14] In addition, vehicle retrofit costs to allow for gaseous fuel use in existing vehicles must also be considered, compared to the convenience of using ethanol or biodiesel blends with essentially no vehicle modification costs in many cases. (See Chapter 15.) Since modern automobiles are often used for a 12-year timeframe, the turnover in a national vehicle fleet will be slow, and the ability to use existing vehicles in a biofuel implementation strategy will allow for a much more rapid impact on a nation's overall transportation fuel use.

In contrast with biogas, it is often possible to find at least one type of fuel option at a gasoline/diesel refueling station that can be replaced with a biofuel pump, entailing relatively low costs for changing over an existing pump/storage tank to accommodate biofuel storage (costs for this type of retrofit are estimated to be around €830, or $1,000). For those refueling stations where it is felt that an existing petroleum product cannot be dropped to accommodate a biofuel, costs will be distinctly higher if new underground storage tanks must be installed—for example, this cost is estimated to be around €18,000 ($22,000) for an 11,000-liter underground storage tank.[15]

14.4.2 Refueling Infrastructure for Flex-Fuel and Dedicated Biofuel Vehicles

In Brazil, 29,646 out of a total of 31,979 vehicle-fueling stations sell "neat" ethanol (actually hydrous ethanol that contains 4 percent water) for use in flexible-fuel vehicles (FFVs) and pure alcohol vehicles.[16] And in the United States, approximately 590 fueling stations out of 168,987 sell E85, a mix of 85 percent ethanol and 15 percent gasoline for use in FFVs. About 6 million FFVs on North American roads are able to use this fuel, although it is worth noting that few of these actually use E85.[17]

In terms of market applicability, pure ethanol can be used in FFVs in warm tropical and subtropical climates like Brazil, whereas E85 is targeted to (and particularly appropriate for) markets with colder climates, such as the United States and Europe. Ford Motor Company, Volvo, and Saab have all announced plans to market E85 vehicles in Germany and elsewhere in Europe.

Germany has proven that pure biodiesel fuel (B100) can be used in existing diesel engines with some minor refitting, concerning mostly seals. B100 has received a fuel tax exemption in Germany, where more than 1,500 fueling stations now sell the fuel (Note that Europe's new "EURO V" regulations will require more stringent engine performance criteria for the European automotive industry. There are questions whether B100 will be compatible with the new particulate and NO_x standards, although B10 blends will likely comply.

14.4.3 Ethanol Transportation Infrastructure

Brazil

Brazil is increasingly interested in building infrastructure to export ethanol internationally, whereas in the United States, ethanol infrastructure is driven almost exclusively by the domestic market. As a result, Brazil’s ethanol sector has given some consideration to export issues and infrastructure requirements. This includes investments in the construction of larger maritime terminals or greater storage capacity (which allows for regulation of the supply), as well as the construction of pipelines to minimize transportation costs.

The infrastructure required to facilitate ethanol export demands the interconnection (via waterway) of producers from Brazil’s southwest with storage facilities in São Paulo state, which then connect to ports in Rio de Janeiro and São Sebastiao. Upon completion of 550 kilometers of pipelines in 2010, the capacity of these two ports will reach 4 million cubic meters per year. All civil works required to put the infrastructure in place are contingent on a €347 million ($420 million) investment.[18] It is worth mentioning that Brazil’s ethanol exports in the last two years have surpassed two billion liters, and only modest infrastructure has been added for ethanol handling.

Between 2008 and 2010, €132 million ($160 million) will be invested in the waterway infrastructure in Brazil’s midwest, as well as west of São Paulo state. This will entail the construction of 4–5 storage terminals and 90 kilometers of pipelines. Potential environmental concerns regarding these plans are addressed in Chapter 13.

The Brazilian oil company Petrobras plans to reach an export capacity of 2 billion liters per year of ethanol in 2005–07, with 1.2 billion liters per year in the southeast and 0.4 billion liters per year each in the south and northeast.[19] The goal is to reach 5.4 billion liters per year between 2008 and 2009, and 9.4 billion liters in 2010. It is expected that world ethanol production, which was estimated at 38.2 billion liters in 2004, will escalate to 60 billion liters in 2010.[20] Petrobras’s expected investments do not include the acquisition of barges, rail cars, and trucks, or the shipment fees associated with each transportation mode. On a volume basis, assuming 20 years of operation and solely considering the upfront investment costs (not future operational costs), the total investment equates to €2.50 ($3) per 1,000 liters of ethanol.

The transportation costs charged by Petrobras range from €3.56-€13.65 ($4.31–$16.52) per 1,000 liters, depending on the pipeline used and distance. The oil company charges external users a monthly fee of €3.47 ($4.20) per 1,000 liters to store alcohol in its facilities.[21] This adds a significant cost to ethanol since, on average, it is stored for six months to guarantee the supply during the off-harvesting season. Thus, the storage cost of half the annual amount produced is around €21 ($25) per 1,000 liters, yielding an average cost of €10.30 ($12.50) per 1,000 liters for all ethanol commercialized. The producer’s price of ethanol in São Paulo in 2005 was €288 ($348) per 1,000 liters, and its retail price was €456 ($551) per 1,000 liters. A rough estimate of distribution costs is obtained by subtracting 29.65 percent in taxes plus the producer’s cost from the retail price. Accordingly, €33 ($40) per 1,000 liters corresponds to freight costs in São Paulo.

Part of the ethanol consumed domestically in Brazil is mixed with gasoline, while the remainder is used as a “neat” fuel. Therefore, the ethanol produced in sugar mills/distilleries needs to be transported to distribution terminals that distribute the gasoline/ethanol mix and the neat fuel ethanol to the retail market. Although railroad is more cost effective than road transport to transfer ethanol between producers and distribution terminals, this option is seldom available due to the limited availability of rail transport and the significant upfront investments required for this infrastructure. As a result, distribution between the terminals and the retailers relies primarily on tanker trucks.

Petrobras was responsible for around 20 percent of Brazil's ethanol sales in 2003.[22] In 2003, the company owned 51 distribution terminals and shared nine other terminals with several users. Petrobras also used 11 third-party storage facilities and delivered the fuel to their own 7,200 retail stations, which also sell gasoline/ethanol mix and diesel.

Petrobras has extensive experience with ethanol logistics, including pipeline transport, and is an example of a large-scale distribution biofuels infrastructure. Currently, the company operates eight storage facilities. Seven are located in the southeast region of Brazil, and five of these are in São Paulo state. These facilities contain tanks to collect and store ethanol and are interconnected by railroads to three maritime ports on the Atlantic Ocean (Rio de Janeiro, Santos, and Paranagua). The company also operates an ethanol distribution storage facility in the Brazilian midwest (Alto Taquari), which is connected to its transport network. Transport between the storage facility of Paulinia in São Paulo and Rio de Janeiro is done through a pipeline. In Rio de Janeiro, the product reaches a maritime terminal from where it can then be exported to international markets via ship.

Currently, most Brazilian ethanol is transported within the country by tanker trucks. Of the 11 facilities operated by Transpetro (the transportation branch of Petrobras), eight depend on trucks, three are connected to pipelines, and two are connected to railroads.[23]

United States

In 2005, U.S. ethanol consumption, including both E85 and ethanol mixed in gasoline as an oxygenate, was 14.8 billion liters.[24] By 2010, it is projected to reach 19.3 billion liters.[25] This increase is expected to occur through both the expansion of existing facilities and the construction of new facilities. However, the 2010 projection is conservative: over the past six years, growth in U.S. ethanol consumption averaged 14 percent annually, whereas the projection accounts for only 8 percent annual growth. Due to this disparity, it is worth speculating about U.S. infrastructure needs associated with a much larger supply of ethanol by 2010—of as much as 37.8 billion liters per year.

The investment needed to put in place the equipment and convert existing storage tanks to ethanol is €127 million ($154 million) for the low-end projection of 19.3 billion liters and €172 million ($208 million) for the high-end projection of 37.8 billion liters. In addition, investments in the retail infrastructure to enable the mixing of ethanol and gasoline are needed. This would amount to €122 ($148 million) for the low-end scenario and €238 million ($288 million) for the high-end scenario.[26] (See Table 14–4.)

Table 14–4. Investments and Operational Costs Associated with Expanding U.S. Ethanol Production by 3.7 Billion Liters

Investment Requirements	
Equipment & storage	€127 million ($154 million)
Retail infrastructure	€122million ($148 million)
Operational costs	€323 million ($390 million)
Breakdown of operational costs	
Shipment by barges and ships	€98 ($118) million
Additional 54,832 rail cars	€128 ($155) million

Additional 399,375 truck shipments	€97 ($117) million

Source: See Endnote 26 for this chapter.

After completion, the infrastructure associated with the low-end production scenario will rely on 59 percent of the terminals installed in ethanol distribution centers. About 25 percent of these terminals will have naval connections and 26 percent will be connected through railroads. In comparison, the infrastructure associated with the high-end projection will rely on 85 percent of the terminals installed in ethanol distribution centers. About 19 percent of these terminals will have naval connections and 20 percent will be connected through railroads.

Operational costs are also part of the investments associated with the consumption of 19.3 billion liters of ethanol in 2010. An additional 3.7 billion liters produced in 2010 will cost €98 ($118) million in freight charges associated with shipment by barges and ships.[27] With regard to ethanol transport by railroads in 2010, the expenses associated with freight for 54,832 rail cars amount to €128 million ($155 million). Finally, 399,375 intra-regional truck shipments will cost €97 million ($117 million). Thus, total freight charges in 2010 (for the low-end scenario) amount to €320 million ($387 million).

Increasing the transport of ethanol also demands purchasing new transportation equipment. Table 14–5 shows freight and new equipment costs for the two ethanol production scenarios for 2010 (19.3 billion liters and 38.7 billion liters).[28]

Table 14–5. Transportation Costs for Two Ethanol Production Scenarios in the United States, 2010

Transportation Mode	**Freight**		**Equipment Purchased**	
	Annual Costs (million Euros)	**Description**	**Cost** (million Euros)	**Description**
Low-end scenario (19.3 billion liters)				
Barges and ships	98	3.7 million cubic meters; 726 barge trips	28	21 barges
Railroad	128	55,000 rail cars loaded	127	2,549 tanker cars
Trucks	97	399,000 shipments	24	254 tractor trailers
High-end scenario (37.8 billion liters)				
Barges and ships	134	5.4 billion liters; 1,559 barge trips	55	42 barges
Railroad	165	73,000 rail cars loaded	172	3,472 tanker cars
Trucks	170	804,000 shipments	45	

	563 tractor trailers

Source: See Endnote 28 for this chapter.

The final use of ethanol also affects the transportation cost of the fuel. Although part of the ethanol is mixed with gasoline, it is possible to offer pure ethanol at the pumps. In the United States, most of the ethanol consumed is mixed in gasoline. About 90 percent of the ethanol is used as a 10 percent blend in gasoline and 10 percent is used as an 85 percent blend of ethanol in gasoline in E85 fuels.[29]

The world's two largest ethanol producers, Brazil and the United States, have a spatially concentrated fuel production system and rely on inter-modal distribution to transport the biofuel. The costs of transportation are estimated in Table 14–6.[30] In Brazil, 85 percent of ethanol production is located in the mid-south region, but 33 percent of the consumption occurs in states that do not produce ethanol.[31] In the United States, 88 percent of ethanol production is located in the midwest, while the major consumers are on the east and west coasts.[32] The fuel is transported by barge along the Mississippi River to New Orleans, then transported to the northeast and west coast by ship. Therefore, in both countries, a distribution infrastructure exists for the transportation of ethanol.

Table 14–6. Ethanol Transportation Costs in the United States and Brazil

Transportation Mode (Cost-Effective Distance[a])	**Cost (Euros per cubic meter)**	
	United States	Brazil[b]
Water (including ocean and river barge)	80–25	10
Short trucking (less than 300 km)	8–17	26
Long distance trucking (more than 300 km)	17–83	
Rail (more than 500 km)	17–40	17

Notes: (a) cost-effective distance is based on U.S. estimates; (b) assuming that specific gravity is 0.789 g/ml at 20°C, and exchange rate is R$2.83/Euro
Source: See Endnote 30 for this chapter.

Although pipeline transport is the cheapest way to transport liquid fuels, biofuels face several challenges in this regard. If ethanol/gasoline blends are to be transported in pipelines used routinely only for petroleum products, there is a concern that "phase separation" can occur, where the ethanol pulls itself out of the blend as a separated ethanol water strata. (This is of greater concern in cold winter conditions, since phase separation occurs more readily at cooler fluid temperatures.) When "neat" (pure) ethanol is to be transported, if it contains a small amount of water, the water component can contribute to corrosion inside the pipe, since petroleum pipelines are generally made with steel that is not resistant to water corrosion (because petroleum does not contain water).

14.4.4 Biodiesel Transportation Infrastructure

Biodiesel fuel is easier to transport and store than ethanol because it can use the same infrastructure as diesel. However, because of the smaller scale of production, biodiesel is usually transported by trucks, which are not as cost competitive as pipelines that transport diesel. Transportation costs for biodiesel in the United States can be as high as €330 ($440) per 1,000 liters.[33]

Currently, 1,900 refueling stations in Germany sell pure biodiesel in the form of rapeseed methyl ester (so-called RME100). Much of the fossil diesel sold in Germany contains a blend of 2 percent RME, where the blending is done by the petroleum refineries. The goal is to increase this amount to 5 percent RME over the next four years. This is likely to result in some competition in the German biodiesel distribution network between refiners who need biodiesel for use in low-level blends, and the refueling stations that need biodiesel for RME100.

With the phase-in of ultra low sulfur fuel, one concern with biodiesel is that existing pipelines and storage tanks may have a build-up of sulfur residues on their internal surfaces that could be freed up by the solvent action of biodiesel, potentially raising the sulfur content of diesel/biodiesel blends above allowable levels. This may be only a temporary problem in a fuel changeover time period when new low sulfur requirements take effect, but an assessment of this concern may be needed to determine the potential severity of the problem and possible solutions.

14.5 International Transport Considerations

Increased global trade in biomass and biofuels would necessitate consideration of the infrastructure and related requirements for international transport, particularly by sea. International bioenergy trade can include direct transport of biomass materials (chips, logs, bales, etc), intermediate energy carriers (such as bio-oil or charcoal), or high-quality energy carriers (e.g. ethanol, methanol, Fischer-Tropsch liquids, and hydrogen). In addition to factors like the production method of biomass, the type of transport and the order and choice of pretreatment operations are of importance.

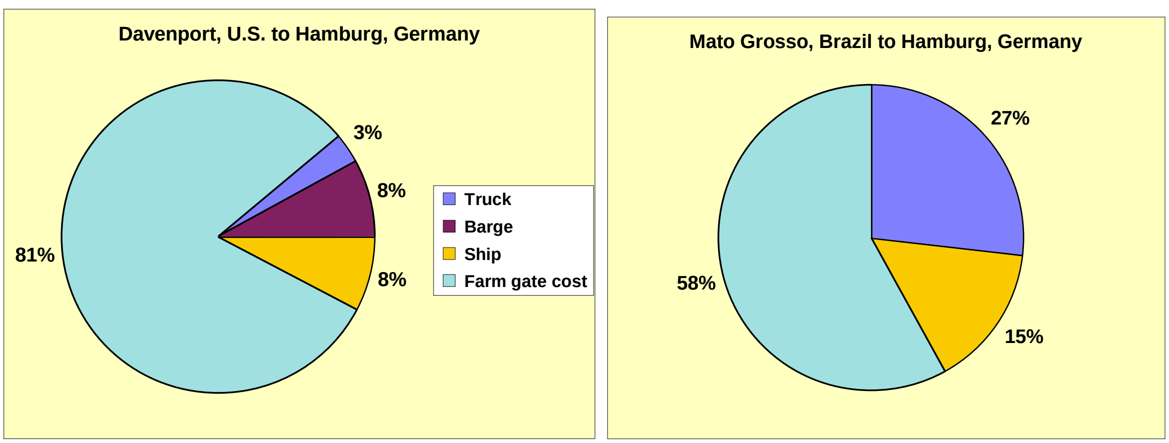
Studies of intercontinental biofuels trade, and even of bulk transport of wood, have found that maritime transport of these commodities could be economically feasible, as it does not appear that dramatic energy losses would be incurred. For example, exporting forest residues some 1,500 kilometers from the Baltic region to the Netherlands—including inland transport and transfer, and using smaller-size vessels—results in an overall energy use of 5 percent of the energy content of the biomass transported. And exporting (cultivated) wood some 10,000 kilometers from Latin America to the Netherlands—accounting for inland transport and transfer, and using large-size vessels—uses about 10 percent of the energy content of the biomass.[34]

In a recent study, various options for transporting raw or processed biomass were evaluated, including direct transport of woody biomass (chips, logs, or bales), an intermediate energy carrier (pyrolysis oil), and a high quality energy carrier (methanol). In general, Latin-American biomass is cheaper than that in Europe. However, this financial advantage is counteracted by the higher costs for long-distance ship transport. The most favorable approaches are those with a high energy density, such as pellets, logs, and liquid carriers. Long-distance transport of wood chips (e.g., by ship) is generally not desirable because chips have a relatively low bulk density and are vulnerable to fungi deterioration due to their moisture content and large specific surface area.[35]

International transport of biomass (or energy carriers from biomass) is feasible from both an energy and cost point of view. Such systems are in fact current practice: large paper and pulp complexes import wood from all over the world. Of course, when feedstocks such as wood are considered, trade-offs should be weighed between producing the biofuel where the feedstock is harvested (and then transporting or importing it to the country where it will be used), versus importing just the wood feedstock (and then converting it into biofuels or electricity in the country where the end products are to be consumed).

The cost implications for using international transport infrastructure to deliver biomass feedstocks for biofuel production are illustrated in Figure 14–2.[36] The charts compare the farm gate and international transport costs for delivering soybeans to Hamburg, Germany (for use in biodiesel) from the United States versus Brazil. The average cost of transporting soybeans by trucks is 3.32 eurocents (4.02 U.S. cents) per kilometer in Brazil and 3.37 eurocents (4.08 U.S. cents) per kilometer in the United States.[37] The final cost of producing and delivering soybeans to Germany is €231 ($279) per tonne from the United States and €248 ($300) per tonne from Brazil. However, the farm-gate value is €187 ($226) per tonne in the U.S. but only €145 ($175) per tonne in Brazil. This illustrates the extent to which transportation costs versus feedstock production costs contribute to the final delivered cost of biofuel feedstock.

Figure 14–2. Transport Costs for Delivering Soybeans to Germany from the U.S. vs. Brazil



14.6 Conclusion

Existing experience with first-generation feedstock and conversion technologies provides useful insight into the infrastructure needed for next-generation cellulose-based biofuel production. Infrastructure will be needed for the transport of feedstock and biofuels, as well as for feedstock conversion facilities, biofuel storage, and vehicle refueling.

Current infrastructure available for the use of agricultural and forestry resources needs to be evaluated to determine what expansion and refinements are needed if renewable biomass resources are to play an expanding role in providing sustainable transportation fuel supplies. Some of the larger first-generation biofuel facilities require in the vicinity of 3,000 tonnes per day of feedstock (such as “dry mills” that produce ethanol from corn); and next-generation facilities are envisioned that would call for 6,000 tonnes per day or more of feedstock (such as gasification/Fischer-Tropsch facilities that will convert wood to synthetic diesel). To enable the expansion of biofuel production in such facilities, as well as provide for associated distribution requirements, it is clear that substantial infrastructure planning and development will be needed.

Chapter 15. Vehicle and Engine Technologies

15.1 Introduction

This chapter provides an overview of the main technological issues related to the current and potential use of biofuels in motor vehicles. Although the primary focus here is on ethanol and biodiesel, use of straight vegetable oils (SVO), dimethyl ether (DME), biomass-to-liquid fuels (BTL), and ethyl tertiary butyl ether (ETBE) is also discussed. Biogas, methanol, and hydrogen are addressed very briefly as well.

15.2 Ethanol

Fuel-grade ethanol, produced from biomass, has been considered a suitable automotive fuel for nearly a century, particularly for vehicles equipped with spark-ignition engines (technically referred to as Otto cycle engines, but commonly known as gasoline engines). It is by far the most popular biofuel available commercially today. Brazil and the United States are the world leaders in fuel ethanol use, though many other countries, including Australia, Canada, China, Colombia, India, Paraguay, South Africa, Sweden, and Thailand, have also introduced it in the fuel market. Ethanol has long been regarded as a top fuel for car and motorcycle racing in Brazil and, starting in 2007, it will be the standard fuel for the IndyCar series in the United States as well.[1]

Corrosion problems have been avoided with the adoption of suitable fuel ethanol specifications such as the Brazilian ANP[*] or the U.S. ASTM[†] standards, as well as care to avoid fuel contamination, particularly with water. Depending on the characteristics of the ethanol, treatment with corrosion inhibitors has also been adopted.

Because ethanol has a solvent effect, it will clean existing deposits from a vehicle's fuel system when used either as a "neat" fuel (in pure form) or as a blending agent in vehicles that have previously run on gasoline or diesel oil. In cases where ethanol blends are being introduced into existing vehicle fleets, replacing the fuel filter at shorter intervals than the standard service periods is recommended, particularly during the first few months of operation with these blends. The vehicle's spark plugs should also be checked and (if necessary) cleaned during the initial phase of operation with ethanol blends. This will avoid premature clogging of filters and the buildup of combustion chamber deposits on the spark plugs, thereby facilitating trouble-free engine operation.

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[*] Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) is the Brazilian governmental agency responsible for fuel quality specification.
[†] The American Society for Testing and Materials (ASTM) elaborates fuel quality specifications in the United States.

15.2.1 Ethanol Use in Spark-Ignition Engines

Low Ethanol Content Gasoline Blends

Blending anhydrous (i.e., essentially water free) ethanol to gasoline at a ratio of 1:10 by volume (E10) has been the most popular and fastest way of introducing fuel ethanol in the marketplace. Extensive international experience demonstrates that, in general, such blends do not require engine tuning or vehicle modifications. And since most of the materials that have been used by the motor industry over the last two decades are E10 compatible, substitution of parts is not usually required.

The use of E10 has been covered under warranty by all manufacturers selling light-duty vehicles in the United States and Canada for many years, and it is becoming common practice elsewhere. Because European Union (EU) fuel quality regulations have limited the ethanol content to 5 percent (E5) or less, automakers have typically restricted the warranty coverage of vehicles sold in the EU to this level. An initiative launched by Volkswagen and DaimlerChrysler in February 2006 opts for E10 in new vehicles in Europe.

In general, blends up to E10 do not result in perceived changes in performance or driveability. Maintenance requirements also do not differ from those with gasoline use. Since the variation in fuel consumption is very small (0–2 percent on average), and use of these blends is considered environmentally friendly, public reaction tends to be positive.[2]

Gasoline Blends Beyond E10

In Brazil, all brands of automotive gasoline contain anhydrous ethanol in the range of 20–25 percent (E20–E25),[*] and manufacturers of cars and two-wheel vehicles have been customizing products to these blends for more than 25 years. Independent importers, meanwhile, have been adapting foreign vehicles by using ethanol-compatible materials in the fuel system and by tuning the engines (mainly the fuel delivery and ignition timing) for a mid-range point, usually at the 22 percent ethanol level (E22). This customization has resulted in good driveability and performance, with fuel consumption comparable to gasoline operation.

Due to the availability of on-board electronic engine management systems capable of self-adjusting to different engine operation conditions, and to the standard use of ethanol-compatible materials, imported vehicles equipped with gasoline-only engines have been marketed in Brazil since 1998. According to an engineering consulting company specialized in conversion to E20/E25, these vehicles have presented trouble-free operation.[3] In all of the above cases, full warranty coverage for the vehicles has been provided by either the manufacturer or the import company.

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[*] Brazilian law (Lei Nº 8.723/1993) and regulations define that ethanol content in gasoline shall be within the 20–25 percent range. Due to the inherent characteristics of the blending process, a tolerance of ± 1 percent is allowed; therefore, the accepted range is 19–26 percent. The actual ethanol content is established by the Inter-ministerial Sugar and Ethanol Council (CIMA) based on supply-demand analysis; for the last three years it has been 25 percent.

Elsewhere, as in Australia and the U.S. state of Minnesota, there have been initiatives to implement regular use of blends beyond E10 but generally limited to E20. Existing vehicles in regular use may eventually need to have parts of the fuel delivery system and engine changed, and the engine tuned for trouble-free operation and conformation with emissions standards. Because certain materials such as aluminum, magnesium, zinc, lead, brass, natural rubber, nylon, and polyvinyl chloride (PVC) may degrade after long-term contact with high levels of ethanol, a careful evaluation of vehicle and engine customization needs for a particular blend is recommended before routine use is initiated. Ethanol-compatible parts should be used in the customization process. Depending on the particular customization requirements, costs may run from a few euros for substitution of fuel lines to more than €500 ($605) if the fuel-supply system is fully upgraded (fuel lines, tank, pump, filter, etc).

A number of automakers have been manufacturing E20-compatible versions of their vehicles, but few have declared this publicly. One exception is Ford Motor Company, which announced in October 2005 that it would supply an E20-compatible Focus model for the Thai market.[4] Ford's position may well become a trend in the industry and foster additional E20 programs.

Flexible-Fuel Vehicles

Gasoline blends containing 85 percent anhydrous ethanol (E85) have been used in the United States since 1992—and more recently in Sweden and Canada—in so-called flexible-fuel vehicles (FFVs). These vehicles are specially designed to run on straight gasoline or any gasoline-ethanol blend up to E85, from a single tank. The technology is based on sensors in the fuel system that automatically recognize the ethanol level in the fuel. The engine's electronic control unit then self-calibrates for the best possible operation; if ethanol is not present, the engine will self-calibrate to gasoline-only operation. The process is instantaneous and undetectable by the vehicle driver. The main reason to limit ethanol content to 85 percent is to enhance volatility conditions for cold start, particularly in cold climates, since the technology does not use any cold start ancillary system.

As of February 2006, there were an estimated six million E85 FFVs on the road, with the vast majority in the United States and a small share in Sweden and Canada. Ford, General Motors, DaimlerChrysler, Mazda, and Nissan all offer E85 FFVs as standard vehicle versions.[5] Ford has announced plans to launch the United Kingdom's first E85 FFV in 2006, to be sold initially as a fleet vehicle to government agencies.[6]

In 2003, a variant of the E85 FFV technology was unveiled in Brazil. Instead of straight gasoline, the technology is capable of operating either within the E20/E25 range, with hydrous ethanol (E100) exclusively, or with any blend of E20/E25 and E100. In this technology, the ethanol sensors used in the E85 versions are replaced with an advanced software component in the engine's electronic control unit, which uses inputs from conventional oxygen sensors in the exhaust system (lambda sensors) and self-calibrates the engine to fuel requirements.

The E100 FFVs have become a sales phenomenon since their introduction in the Brazilian marketplace, in part because E100 is significantly less expensive than E20/E25 in much of the country. Unlike elsewhere in the world, both E100 and E20/E25 can be found easily at more than 29,000 retail stations throughout Brazil. As interest in importing the technology grows worldwide, a second generation is being developed that extends the operational range from straight gasoline to E100. Volkswagen, Fiat, General Motors, Ford, Renault, Citroen, and Peugeot are all offering E100 FFVs as standard versions, and Toyota and Honda are expected to offer similar versions in 2006. As of December 2005, more than 70 percent of new light-duty vehicle sales in Brazil were E100 FFVs, and cumulative sales of the vehicles have totaled more than 1.3 million since March 2003.[7]

This technology has proved feasible in Brazil in large part because the warm climate allows blending of hydrous ethanol to E20/E25 without the risk of phase separation. Yet even at lower temperatures, cold start can be accomplished with automatic injection of E20/E25 stored in a small tank under the hood. International automotive suppliers Bosch, Delphi, and Magneti Marelli are all developing new cold start systems that will not require the auxiliary E20/E25 tank. This new technology setup is based on sensors that monitor engine and ambient temperatures during cold start, as well as automatically heated fuel injectors equipped with multi-spray injection nozzles, new spark plugs, and control software. Industry sources believe the new technology will be available commercially in 2007. The concept could also be applied in the E85 FFVs and allow for increased ethanol content in the blend.

FFVs are built with ethanol-compatible materials, have shown proven reliability, come with manufacturer's warranties, and cost roughly the same to maintain as gasoline vehicles. Because of ethanol's lower energy content and the tendency of car manufacturers not to take full advantage of the fuel's combustion properties, fuel consumption with either E85 or E100 is higher than with gasoline or E20/E25.* FFVs have demonstrated an average drop in fuel economy in the range of 25–30 percent, depending on vehicle/engine characteristics; however, it should be noted that these figures can be considerably improved at moderate costs with existing technology.

On the other hand, performance tends to improve with both E85 and E100, though the degree of improvement depends on power train characteristics. For standard FFVs, a 5 percent increase in power is not unusual; however, for a more advanced FFV concept, such as Saab's, which uses a "smart" turbocharging system to boost the turbo pressure as the ethanol content increases, the power increase can near 20 percent.

Manufacturing FFVs does not add much to the cost of the vehicle. In both the United States and Brazil, the price of FFVs has been very similar to that of baseline gasoline vehicles, and in some cases the same.

Dedicated Ethanol Vehicles

While FFV engines must retain dual-fuel capability, dedicated ethanol vehicles can take advantage of the combustion characteristics of ethanol and therefore perform better with lower fuel consumption. An increase in the engine compression ratio† of up to 13.5:1 (versus approximately 9:1 to 10:1 for conventional gasoline engines) allows for improved fuel combustion efficiency that partially offsets ethanol's lower energy content.

Most of the experience with dedicated ethanol technology comes from Brazil, where more than five million units have been sold since 1979.[8] Initially equipped with carburetors and old-style ignition advance systems, and upgraded with electronic fuel injection and mapped electronic ignition since 1991, ethanol vehicles have demonstrated proven reliability, good driveability, and

* Fuel combustion properties include high octane, high latent heat of vaporization, and high flame speed.
† Refers to the air-fuel mixture compression level in the engine's cylinders and combustion chambers; the higher the compression ratio, the more efficient the combustion process is likely to be.

low maintenance costs. On average, fuel consumption has been 25 percent lower than for equivalent E20/E25 fueled versions. Volkswagen, Fiat, General Motors, and Ford have all produced dedicated ethanol versions for more than 25 years, with full warranty coverage. Maintenance costs do not differ significantly from standard gasoline vehicles and, according to anecdotal reports, can actually be lower because of ethanol's ability to keep the fuel system and engine clean.

Growing interest in ethanol in the United States, particularly since 2000, has stimulated research into high-efficiency engine technology. The U.S. Environmental Protection Agency, through its National Vehicle and Emissions Laboratory, has conducted trials with a "neat" ethanol port fuel-injected turbocharged engine, with a compression ratio of 19.5:1. The study concluded that high combustion efficiencies *can* be achieved, yielding up to 20 percent fuel-economy improvement over baseline gasoline engines—results comparable to diesel engines.[9] This suggests that the concept could become a benchmark for dedicated ethanol engines whose use could also be extended to medium- and heavy-duty vehicles.

15.2.2 Ethanol Use in Compression-Ignition Engines

Diesel Modified Engines

Since the 1980s, attempts have been made to use ethanol in compression-ignition engines (diesel engines), though this application has been limited. The most successful experience has been in Sweden, where approximately 500 urban buses are operating on a mixture of 95 percent hydrous ethanol and 5 percent of an ignition additive known as "Beraid."[10] The additive is used to promote fuel ignition, since ethanol is difficult to ignite in a compression ignition engine.

An initiative of the auto manufacturer Scania and the municipality of Stockholm, Sweden's first ethanol buses began operating in 1990, and were introduced as a way to meet environmental requirements for cleaner fuels. The buses have been used mainly for inner-city service, where the environmental gains (in particular the reduction in particulate emissions) are most noticeable. The power train is based on a diesel engine converted to ethanol through the following modifications: an increase in the compression ratio from 18:1 to 24:1; use of fuel injectors and a fuel pump with higher volumetric capacity; optimization of the ignition advance; increase in fuel tank volume; and use of ethanol-compatible materials in the fuel delivery system.

Scania reported a drop in fuel economy on the order of 40–50 percent for the ethanol buses relative to diesel, while operational performance was considered adequate.[11] SL, the bus operating company, reported higher maintenance costs for the ethanol buses as well.

In the United States, Detroit Diesel Company (DDC) has converted a two-stroke diesel engine to run on alcohol using modifications similar to Scania's, except for the substitution of a glow plug to start ignition since fuel ignition additives were not considered. A one-year trial in Peoria, Illinois, with two vehicles equipped with the ethanol engine showed results similar to those with the Scania buses. The incremental maintenance cost during this period was close to 5 percent for one vehicle and up to 20 percent for the second.[12] Both Scania and DDC have provided full warranty coverage for the vehicles.

Diesel-Ethanol Blends

Although ethanol's ability to blend with diesel oil is not as good as with gasoline, ethanol can be emulsified with diesel oil and the resulting blend can be used in a standard diesel engine. International experience has shown that although diesel-ethanol blends can contain up to 15 percent ethanol, a good compromise in terms of fuel economy, performance, driveability and emissions can be achieved with about 7 percent. In this case, an average fuel economy loss of approximately 2 percent might be expected. Also, depending on power train characteristics and in-service conditions, operational performance might be lowered slightly.

Diesel-ethanol blends and the particular additive package used to prepare the emulsion need to be evaluated carefully before use, since some fuel delivery systems, such as the rotary-type fuel pump, may be very sensitive to the presence of ethanol and result in premature wear. Moreover, some parts, such as fuel filters and fuel lines, may need to be made ethanol-compatible. Special care with water contamination should also be taken to avoid phase separation, since the entry of dissociated water into the combustion chamber may damage the engine.

Dual-Fuel Operation

One approach that uses diesel and ethanol simultaneously, without having to blend the fuels, is "fumigation," whereby a carburetor, fuel injector, heated vaporizer, or mist generator is used to meter ethanol into the engine's air intake manifold. Fumigation of up to 50 percent ethanol has been reported.[13] Injection of ethanol directly into the cylinder of an engine with an increased compression ratio and a glow plug to assist with ignition is another approach that has been tested, showing that up to 90 percent diesel displacement could be achieved.[14] In both cases, an additive such as nitride glycol may be required to allow for lubrication of the mechanical moving parts. Both fumigation and direct injection require an additional fuel handling system for ethanol that results in incremental hardware costs. An interesting characteristic of these technologies is that both permit running completely on diesel fuel in the event of a disruption in the ethanol supply.

Commercial success of these technologies has been limited, mainly due to the complexity of the existing systems. However, advances in on-board electronics, sensors, and digital engine operation mapping, in addition to the possibility of precise ethanol metering at selected engine operating modes, could help simplify the hardware, optimize the benefits of ethanol use, and reduce costs.

Conversion to Spark-Ignition Engine

Diesel engines can be converted to spark-ignition engines to enable them to run on ethanol, as has been experienced on several occasions. However, the standard conversion practice, which typically requires a significant reduction in the compression ratio, is not desirable because it significantly lowers the combustion efficiency. Nevertheless, as discussed earlier, a new approach to conversion with a high compression ratio and port injection typical of diesel applications would be advantageous and could foster commercial development of such conversions.

15.3 Biodiesel

Fuel-grade biodiesel is usually defined as a methyl or ethyl ester derived from transesterified vegetable oil or animal fat that conforms to industry specifications. The European Union standard EN 14214 and the U.S. standard ASTM D 6751 have become the international references for the fuel, though a considerable number of other national references exist as well.

One characteristic of biodiesel that must be addressed adequately by users is the fact that it oxidizes much faster than ordinary diesel. Proper care is needed to avoid premature aging during storage. Moisture can also be a problem, resulting in bacteria growth and the formation of corrosive free fatty acids that could have a negative effect on the fuel injection system and the engine itself. Limiting exposure to airborne moisture and water deposits and using suitable additives improves biodiesel's ability to withstand long-term storage.

Biodiesel has been used in two ways in compression ignition engines: as a blend with ordinary diesel, or as a straight fuel. Like ethanol, biodiesel has solvent properties that break down deposits in the fuel supply system; thus, fuel filters may face the risk of premature clogging. Preventive measures, such as those discussed earlier for ethanol, are worth considering.

15.3.1 Biodiesel As Blending Agent

Biodiesel mixes easily and completely with ordinary diesel fuel, at any concentration. In the United States, the 20 percent blend (B20) has been a very popular option, while in France the 30 percent blend (B30) is preferred because of its greater capability to reduce harmful emissions. Most diesel vehicles are able to run on blends of up to B20 with few or no modifications (e.g. substitution of parts containing certain plastics or rubber-like materials), particularly if the vehicle was manufactured after the mid-1990s. As with ethanol, blending has been the easiest and lowest-cost way of introducing biodiesel in the marketplace.

The automotive industry prefers blends of up to 5 percent biodiesel content (B5) for use in existing vehicle fleets because it enhances lubricity, especially of ultra-low-sulfur diesel. In some countries, such as France, all diesel sold routinely contains up to B5.[15] Regarding warranty coverage, most original equipment manufacturers (OEM) tell their customers that use of up to B5 is acceptable, as long as the pure product conforms to an approved quality standard. Many OEM fear that higher blend levels could degrade fuel lines, filters, o-rings, and seals and damage fuel injector orifices, among other potential problems—resulting in leaks and faulty engine operation. Although some OEM leave the risks of biodiesel use to the customer's discretion, others have threatened to void warranties in the event of problems attributable to biodiesel. OEM advice on using biodiesel blends varies widely, however. While some consider a 20 percent blend (B20) acceptable, others will deem anything up to 100 percent biodiesel (B100) acceptable.

Another concern expressed by the automotive industry is the higher viscosity of biodiesel, which at B20 or higher could affect fuel flow and fuel spray in the combustion chamber, particularly in colder conditions. If proper care of fuel handling and use is adopted, however, no problems should be experienced.

Biodiesel's high cetane value (ability to ignite under compression) is considered an advantage because this has a pronounced effect on combustion quality and thus on noise and emissions reduction. Mixing biodiesel with ordinary diesel adds cetane value to the resulting blend.

Despite industry worries and inconsistent warranty coverage, consumption of biodiesel blends has increased steadily, mainly in the European Union (see Chapters 1 and 20). As a result, a growing number of manufacturers have been marketing vehicles equipped with biodiesel-compatible parts and engines.

Depending on product characteristics, which vary based on the type and purity of the feedstock used and on the production process itself, biodiesel shows up to 12 percent lower energy content than ordinary diesel. Therefore, a slight drop in fuel economy and performance might be expected. A comparative study found that on average B20 would result in a decline in fuel economy in the range of 0–6 percent, while a marginal loss of 2 percent in performance was observed.[16] For B5, the change in fuel economy and performance is marginal, in the range of 0–2 percent, and is usually not noticeable.

User feedback suggests that maintenance requirements for diesel engines operating on biodiesel blends of B20 or less are identical to those operating on standard diesel.[17]

15.3.2 Straight Biodiesel

Straight biodiesel (B100) can be used in existing diesel vehicles; however, it may require modification of engine or fuel system components as well as some fine tuning. Biodiesel-compatible materials such as Viton®[*] are required for use with B100 unless specified, particularly in fuel hoses, pump seals, and gaskets. Tuning of fuel injection timing may also be required, depending on engine characteristics. Typically timing needs to be retarded by 1–2 degrees to avoid rough engine operation and minimize nitrogen oxide (NOx) emissions.

Because of its high viscosity, B100 is preferred in warm climate conditions; however, introduction of fuel tank heaters and anti-gel additives has made B100 use possible in very low temperatures.

For existing vehicle fleets, fuel economy with biodiesel may be lowered by up to 15 percent relative to ordinary diesel, while power loss may drop by 7 percent.[18] It should be noted that these figures can be improved for new customized vehicles. Maintenance is generally similar to or less demanding than for ordinary diesel use. In fact, B100 use results in decreased soot deposits in the injectors and combustion chamber. Fuel filter life and oil changes can also be extended somewhat.

15.4 Other Biofuels

15.4.1 Straight Vegetable Oil (SVO)

SVO refers to either new or waste vegetable oil, both of which can be used in diesel engines. Due to its relatively high viscosity (approximately 12 times higher than ordinary diesel), using SVO in unmodified engines can result in poor atomization of the fuel in the combustion chamber, incomplete combustion, coking of the injectors, and accumulation of soot deposits in the piston crown, rings, and lubricating oil.

If SVO is to be used in conjunction with diesel in a dual-fuel mode, necessary modifications include an additional fuel tank for SVO, a system to allow for switching between the two fuels,

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[*] A fluoroelastomer produced by E.I. Dupont de Nemours Company that is well known for its excellent resistance to heat and aggressive fuels and chemicals.

and a heating system for the SVO tank and lines if the vehicle operates in temperatures below 18º Celsius. Under this configuration, the engine is started on diesel and switched over to SVO as soon as it is warmed up. It is then switched back to diesel shortly before being turned off to ensure that it contains no SVO when it is restarted.[19]

Another alternative is to use SVO exclusively. Modifications would include an electric pre-heating system for the fuel (including lines and filters), an upgraded injection system, and the addition of glow plugs in the combustion chamber, since vegetable oil is not highly flammable. The modification can be expensive, reaching a cost of €2,000 ($2,420) or more.[20]

15.4.2 Dimethyl Ether (DME)

DME is a gaseous fuel that can be produced from a variety of sources, including biomass feedstocks such as wood or black liquor synthesis gas. Interest in the fuel is rising in Japan and Europe, as DME is considered a promising substitute for diesel or liquefied petroleum gas (LPG). The vapor pressure of DME is similar to LPG, and it can be contained in a gas cylinder at low pressure because of its ability to change into liquid at approximately 0.5 megapascals (approx. 72 psi) and room temperature. Despite these physical similarities, however, DME differs significantly from LPG in its ability to dissolve most sealing materials used in normal automotive applications. Its application therefore requires use of metal-to-metal sealing or other materials such as Teflon® or graphite.

Experience indicates that DME is an environmentally advantageous substitute for diesel, particularly in buses and urban delivery trucks. DME has a relatively high energy density (about 80 percent that of diesel), a high cetane value (55–60), and near-zero sulfur and aromatics content. Combustion of DME in compression ignition engines reduces engine noise levels and emissions considerably, though further NOx reduction may be necessary with after-treatment exhaust gas systems. Significant engineering efforts have been undertaken to customize engines to the fuel, particularly with regard to materials choice, modification of the fuel injection system, and ignition advance. Due to its higher energy density, the driving range with DME can be expected to be higher than with compressed natural gas (CNG). Road trials are under way to evaluate the durability, performance, and practicability of DME propulsion systems.

Large-scale DME production from biomass sources has yet to be accomplished, particularly since the costs are high relative to natural gas.[21] But this may change in the future. On the fossil fuel side, French oil company Total is working with a consortium of nine Japanese companies toward large-scale DME production (6,000 tons per day) from natural gas by 2010.[22]

15.4.3 Biomass-to-Liquid Fuels (BTL)

BTL fuels can be produced through gasification of biomass and the Fischer-Tropsch chemical reaction process. (See Chapter 5.) A suitable alternative to the use of solid biomass feedstocks would be to use biogas (produced from the anaerobic digestion of wet biomass feedstocks such as animal manure) following a similar route of natural gas processing known as gas-to-liquid (GTL). The byproducts of the process include naphta, diesel, and chemical feedstocks. The resulting BTL/GTL diesel can be used as a straight fuel or blended with ordinary diesel or biodiesel.

European companies are particularly interested in this concept since diesel oil accounts for a rising share of the continent's vehicle fleet. A cooperative effort is already in place in Germany involving Volkswagen, DaimlerChrysler, and Choren Industries GmbH and has resulted in an experimental plant producing BTL diesel from forest waste wood under the brand names SunDiesel and SunFuel. Industry sources believe BTL diesel could become a viable commercial fuel by 2010. (See Chapter 5.)

Because BTL/GTL diesel is considered a premium quality fuel due to its very low sulfur concentration (less than 1 part per million), near-zero content of aromatics and toxic substances, and high cetane value (above 70), it could boost the technological prospects for high-efficiency and ultra-low emission engines. With BTL, some companies see the possibility of combining the Otto (gasoline) and Diesel thermodynamic cycles into an optimized combined combustion system, though this concept is still at the research level.

15.4.4 Biogas

Biogas is usually obtained from local waste streams such as sewage treatment plants, landfills, organic industrial waste streams, and digested organic waste. Due to its relatively low methane content (typically 60–70 percent) and high concentration of contaminants, biogas is normally unsuitable for use in vehicles. To be fit for automotive use, its quality needs to be upgraded to as close to CNG as possible. Treatment generally includes removal of carbon dioxide, water, and minor contaminants in order to achieve a minimum methane content, preferably 95 percent.[23]

Treated biogas (TB) can be used in both heavy- and light-duty engines suitable for natural gas. A number of vehicle options can therefore be considered: dedicated CNG or liquefied natural gas (LNG) vehicles, bi-fuel (gasoline/CNG) vehicles, and dual-fuel (LNG/diesel or CNG/diesel) vehicles. Sweden is currently the leading user of biogas in transportation. Its CNG/biogas urban bus fleet comprises approximately 4,500 vehicles, with 45 percent of fuel consumption supplied as biogas.[24] Other countries such as Denmark, Germany, the Netherlands, Sweden, and the United Kingdom have also developed experience in this field.

Because TB is so similar to natural gas, engine performance, driveability, emissions, and maintenance are considered equivalent. Moreover, no differentiation in warranty coverage is required as long as the TB characteristics fulfill the vehicle manufacturer’s requirements.

15.4.5 Methanol

Gasifying biomass is a known method of producing methanol, a product that has already proven itself as a neat fuel or blending agent. Since it has many similarities to ethanol, the technological alternatives for methanol use are similar.

However, due to its higher aggressiveness to materials, higher toxicity, and lower energy content, use of fuel-grade methanol has been considerably lower. Blending has been limited to low levels and, in some cases, is not allowed. Aside from dedicated methanol vehicles produced by car manufacturers, there is only one known case where original equipment manufacturers (OEM) would provide warranty coverage for methanol use.

In the early 1990s, Brazil witnessed an innovative use of methanol for about three years when a localized shortage of E100 led to the introduction of a blend of 60 percent E100, 33 percent methanol, and 7 percent gasoline for use in dedicated ethanol vehicles. The blend has many properties that closely resemble E100 and resulted in similar performance, driveability, emissions, and maintenance.[25]

15.4.6 Ethyl tertiary butyl ether (ETBE)

ETBE is derived from a chemical process that uses approximately 40 percent ethanol and 60 percent isobutylene. It has been used mainly in Europe as a gasoline octane booster and as a partially renewable oxygenated fuel additive. ETBE content in gasoline has generally ranged from 5–15 percent. It is fully compatible with existing engine technologies and gasoline and has no special requirements for automotive use. Although it has lower energy content than gasoline (about 13 percent), the impact of its use on fuel economy has been generally marginal. The most notorious benefit of ETBE use has been its ability to avoid an increase of gasoline volatility and therefore an increase in evaporative emissions.

15.5 Biofuels and Advanced Propulsion Systems

Biofuels can be used efficiently in any of the advanced propulsion systems now reaching the market. These include mainly hybrids and fuel cells. Hybrid vehicle technology that presently relies on fossil fuels (i.e. gasoline, diesel, natural gas, and liquefied petroleum gas) may well take advantage of biofuels' growing availability. For instance, a plug-in hybrid vehicle with a high-efficiency dedicated ethanol engine could present superior performance compared with current commercial versions. Depending on technology characteristics, fossil fuel substitution could reach 100 percent on a volume basis.

Fuel cell technology could also benefit. The availability of multi-fuel on-board reformers that could continuously generate hydrogen out of methanol, ethanol, DME, or TB would enable vehicles to use a combination of conventional and lower-cost fueling systems. Alternatively, commercial-size multi-fuel reformers could generate hydrogen from biofuels on-site at retail stations, avoiding costly hydrogen distribution infrastructure.

15.6 Conclusion

Biofuels have a proven record of technical feasibility. Although ethanol and biodiesel have been the frontrunners in this emerging market, other alternatives are showing significant potential for fossil fuel substitution. Existing automotive technology is in many ways compatible with biofuels, resulting in affordable and efficient solutions for the use of clean and renewable energy. Hybrids and fuel cells, considered to be the ultimate motor vehicle technologies, will have the opportunity to take advantage of the availability and diversity of biofuels. A fabulous synergy between biofuels and automotive technology is likely to be seen in the coming years, resulting in more sustainable transportation alternatives.

What combination of technology and biofuel will prevail in the future? At present, there is no clear answer to this question, as both automotive technologies and biofuels production processes are developing at a fast pace. However, one might expect to see conventional and advanced technologies co-habiting for many years, with biofuels increasing their share in the global market. Nevertheless, significant issues still need to be addressed, including educating people about biofuels, promoting incentives for technological progress, and creating the political will to invest in non-conventional fuel sources.

Chapter 16. Transfer of Technology and Expertise

16.1 Introduction

The development of more efficient and reliable biofuel technologies, and the transfer of this technology and expertise around the world, is key to the expansion of the global market for these fuels. This chapter describes the process of technological change and transfer, with specific application to biofuels. It discusses the main areas where technologies can help boost the development of larger biofuel markets, the role of technology in the development of national biofuels strategies, and the roles of various stakeholders, including governments and the private sector, in the technology transfer process. It concludes with a case study of Brazil's Proálcool program.

16.2 The Technology Change and Transfer Process

The process of transferring biofuel technology and expertise can be best understood as a process of managing technological change. It involves the flows of knowledge, experience, and equipment among different stakeholders, including governments, private sector entities, financial institutions, non-governmental organizations (NGOs), research and educational institutions, and labor unions. It encompasses technological cooperation and the diffusion of technologies both within countries as well as between them. And it involves the process of learning to understand, utilize, and replicate existing biofuel technologies—including the capacity to select and adapt them for local conditions and even to sell them back to the original source as improved technologies.

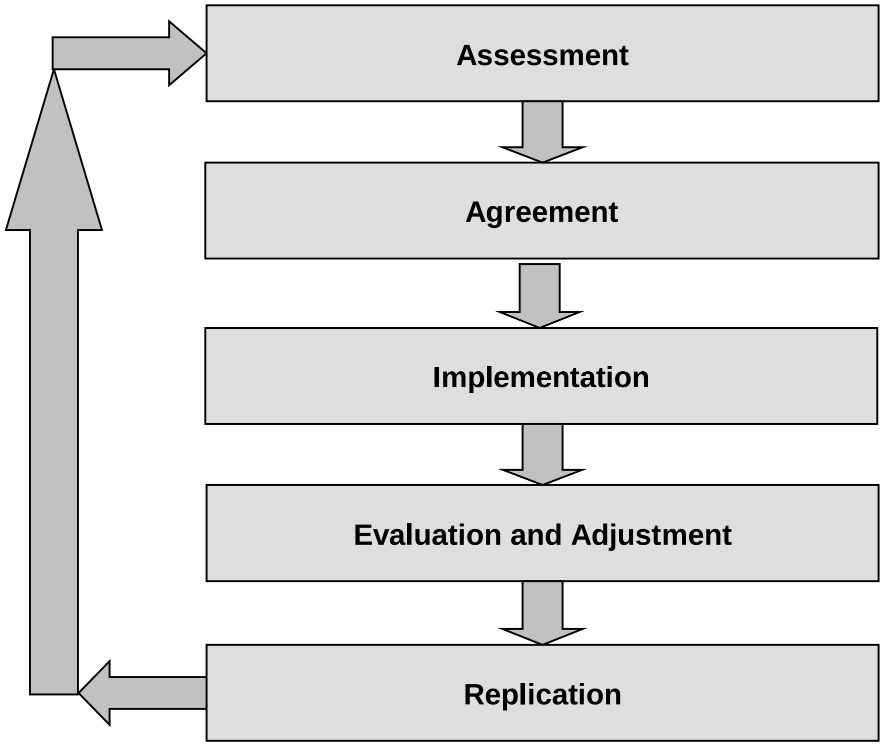
Technology transfer reflects specific actions taken by individuals and organizations. These include:

- acquisition of knowledge and skills by individuals through formal education and on-the-job training;
- assimilation of publicly available knowledge;
- investment and trade decisions made by firms;
- purchase of patent rights and licenses; and
- migration of skilled personnel with knowledge of particular technologies.

Technology flows are also influenced by government policies and by financial aid and development programs. The rate of such flows is affected by the motivations of the relevant stakeholders and by the barriers that impede them—both of which are influenced by government policies, including environmental and climate change policies.

Most technology flows occur in or are driven by the private sector (between commercial parties) though they can also involve the government or community. In most instances, managing technological change and transfer follows five basic stages: assessment and identification of needs, agreement, implementation, evaluation and adjustment, and replication.[1] (See Figure 16–1.)

Figure 16–1. The Five Basic Stages of Technology Transfer



16.3 Biofuel Technology Change and Transfer

As biofuels attract greater commercial and political interest on a global scale, the pace of technological change is accelerating. There is ample evidence that learning curves for these fuels are evolving, driven by expanding markets, changes in design and development, and new information and communication technologies—resulting in sharply lower operational costs and investment requirements.[2]

Nevertheless, ongoing and future developments could substantially improve the energy and cost efficiency of biofuels, based on the relative efficiency of different farming, harvesting, and processing approaches, fuel compositions, and engine technologies. In 2003, Towler et al. identified three main areas where additional research would yield the greatest benefits for biofuels to become competitive with conventional energy sources.[3] These are:

1. *Primary productivity.* Overall, improved productivity helps boost the viability of biomass fuels by lowering crop prices. (See Chapter 7.)

2. *Crop modification.* Increasing processability or the quantity of biomass for processing. Use of biotechnology is a possibility, though this raises concerns about the cost of seeds and the impacts of releasing genetically modified organisms into the environment. (See Chapter 12.)

3. *Conversion process.* New conversion technologies may make the spread of smaller-scale units feasible, thus avoiding the feedstock transportation costs of large plants. The efficiency of biomass gasification and liquid fuels synthesis via Fischer-Tropsch processes can increase, but the overall viability would depend on lower feedstock costs. In all cases, the prospect of co-production of other value-added goods would help the feasibility of biofuels. (See Chapter 5.)

Biofuels technological change has led to a change in the role of key stakeholders. The relative importance of farmers and foresters has increased, for instance, because biofuels derive from agriculture and forestry and the cost of these feedstocks is key to the economics of the fuels.

The transfer of biofuels technology is now a global process. It does not just occur from North to South, but also increasingly within the developing world, and even from South to North. The technology embedded in Brazilian ethanol distilleries, for example, has been transferred to Costa Rica, Kenya, and Paraguay, among other countries. Similarly, technology from Indian distilleries has been brought to Colombia.

16.4 Development of a National Biofuels Strategy

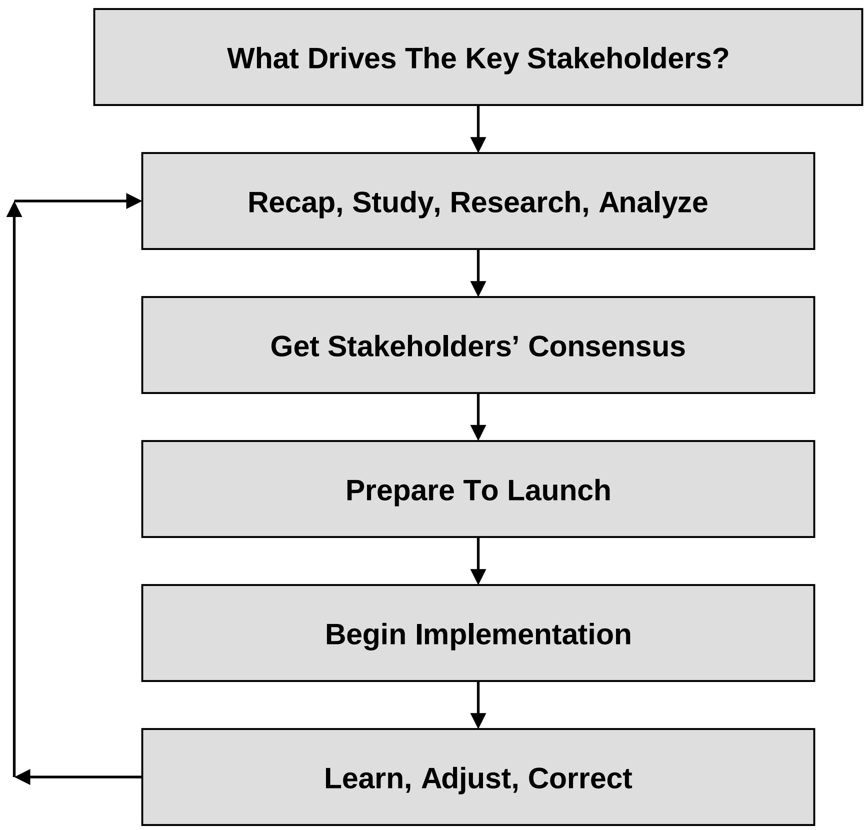
Developing a clear national strategy for biofuels implementation provides continuity to the overall biofuels learning curve, including the technology learning curve. For governments deciding to implement national biofuels programs, it is useful to first consider what drives the key stakeholders in the biofuels economy. It is then important to review, study, research, and analyze technological and other information that has accumulated over the years. These steps pave the way for getting the relevant stakeholders to reach a consensus and commit to implementing a biofuels program, allowing for adjustment and corrections as implementation proceeds.

Figure 16–2 describes the basic elements of a national biofuels program implementation strategy.[4] In one way or another, these processes have unfolded in every country or region that has embarked on a biofuels program: Brazil, the United States, the European Union (EU), Thailand, etc.

Brazil's Proálcool program, launched in response to the oil crises of the 1970s, provides a good example of the implementation process. Brazil had been blending ethanol into gasoline for the previous half century, in part to protect the sugar industry from the vagaries of the international market. Prior to and during the Proálcool launch, stock was taken of both Brazilian and international fuel ethanol technologies. Brazilian consultants and government research institutes were mobilized, as was the country's foreign automobile industry.

In the Brazilian case, the major driver for technology development and transfer was scaling up ethanol production and use. Ethanol technology had to respond to a change in the market, from the beverage and industrial markets to the much larger fuel markets. Ethanol distillery technologies had to resemble oil-refining technologies. Sugar cane agriculture had to expand to meet scaled-up demand for ethanol, via additional land use and particularly through increased yields. And conversion technologies had to be upgraded via technology transfer by working with organizations from numerous countries and within Brazil to improve conversion efficiencies and performance, and to lower ethanol production costs.

Figure 16–2. National Biofuels Program Implementation Strategy



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The Brazil sugar cane case (described later in this chapter) exemplifies the drivers for technology transfer with respect to oil, rural development, and energy diversity. The importance of revisiting the stakeholder consensus, in particular, is evidenced by the disarray of the Proálcool program after the sudden decrease in oil prices in the mid-1980s.

16.5 Role of Government and the Private Sector in Biofuel Technology Transfer

Domestic policies as well as bilateral and multilateral governmental agreements can play a key role in promoting change and transfer in biofuels technology. The development of Brazil's sugarcane ethanol technology, for example, relied on agreements between Brazil and a host of other developing countries. The rate of technological change is also closely linked to biofuel trade and investment, an area influenced by both governments and the private sector.

Depending on their domestic policy choices, governments can either favor or inhibit the development and availability of particular biofuels resources, carriers, or end uses. In Brazil, for instance, political action over time helped to rapidly increase biofuels' share in supplying the country's growing energy needs. (Note that in the 1970s and early 1980s, when Brazil established its nationwide network of ethanol stations and vehicles, it was a ruled by a military dictatorship. Military dictatorships have the ability to implement mandates quickly. In 1985, when the price of oil dropped sharply, a democratic government regained power and struggled for about 10 years to adjust the national ethanol program/mandate in a context of low petroleum fuel prices.)

In the United States, the new energy law signed in July 2005 has provided impetus to a growing biofuels industry. Likewise, the EU directives on biofuels for transportation and on transportation fuels taxation (both from 2003) provided a boost to the biofuel market for transport in EU member states.[5] The EU has not met the target level for biofuels' proportion of fuel energy outlined in 2003; however, the Biomass Action Plan released in early 2006 encourages more demand and supply creation as well as high priority for research into the bio-refinery concept and into next-generation biofuels and continued encouragement of an industry-led biofuels technology. Over the past few years, similar political actions have begun to provide enabling environments for biofuels technologies in Canada, China, Colombia, India, Thailand, and many other countries. (See Chapter 17.)

Governments also play an important role in promoting technological change and transfer through multilateral trade agreements. The Hong Kong meeting of the World Trade Organization's Doha round, concluded in December 2005, if fully implemented, is likely to result in the full liberalization, by 2013, of the EU trade in agricultural-related commodities, including sugar, fuel ethanol, and biodiesel. This is likely to promote technology transfer within the EU and to other countries engaged in international trade of fuel ethanol and biodiesel with the EU. Another government initiative that can foster biofuel technology transfer is the International Energy Agency's Task 40, which deals specifically with the international trade of biofuels. (See Chapter 9.)

Similarly, multilateral environmental agreements highlight the importance of technology transfer to address climate change. Article 4.5 of the United Nations Framework Convention on Climate Change (UNFCCC), for instance, states that participating developed country parties "shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties, to enable them to implement the provisions of the Convention." Article 10c of the Kyoto Protocol to the UNFCCC, coupled with the Protocol's Clean Development Mechanism (CDM) is already promoting technology transfer in biofuels, with one example being support for the development of combined-cycle bagasse-fueled steam and electricity generation in Brazil's sugar and ethanol mills.

Targeted bilateral and multilateral information sharing between countries can also play an important role in information dissemination. For example, Germany and China sponsored a joint workshop in 2003 to share information on new gasification and pyrolysis technologies for producing liquid fuels from biomass.[6]

Notwithstanding the key role of governments, in practice the actual flow of biofuel technologies takes place in the private sector, particularly in the transportation and power generation sectors. While markets can be very imperfect mechanisms, once suitable macroeconomic policies are in place to provide an enabling environment for innovation, markets may determine the choice of technology and the modes of transfer. In the biofuel context, there is ample room for ideas, such as diffusing technologies via transnational commercial networks; business charters for biofuel technological cooperation; biofuel technology investment corporations; and funds financed by private sources in the long term.

One way that government policy can provide an enabling environment for biofuels is by subsidizing biofuel programs, at least initially. Brazil's Proálcool program was launched with the help of lavish subsidies, which were gradually removed over the course of 20 years. In the United States, the use of subsidies has played a key role in fostering ethanol and biodiesel use; these subsidies remain in force today and were extended by the new energy law of 2005. In the EU, the Fuel Taxation Directive allowed member states to remove excise taxes for biofuels for a period of years. In Germany, Spain, and Sweden, they were totally removed. (For more on the role of subsidies, see Chapter 7.)

Other initiatives that can help bring governments and the private sector together are public-private partnerships. At the community level, the main stakeholders are individual citizens, small-scale enterprises, and NGOs concerned with agriculture and forestry.

As the world biofuel market develops, some countries may become either large or surplus producers of these fuels, while others may resort to imports. This could lead to movement of biofuel capital and technologies to the larger producing countries. There is already evidence that this is happening. Novozymes, a Danish company with a strong U.S. presence, is investing in China as that country develops its starch-based ethanol industry, despite concerns over the protection of intellectual property rights. And the London-based biodiesel company D1 Oils Plc. is promoting the use of jatropha oil as biodiesel feedstock in India, the Philippines, and parts of Africa. Brazilian companies, meanwhile, engaged in extensive technology transfer from a variety of countries while developing the Proálcool program. Many of these companies are now selling their own fuel ethanol technologies abroad, getting support from Brazil's government in promoting bilateral cooperation.

16.6 Large-Scale Biofuels Technological Change and Transfer: The Case of Proálcool

Brazil's fuel ethanol program, Proálcool, provides a useful example of large-scale and long-duration biofuel technology change and transfer.[7]

Portuguese colonists introduced sugar cane to Brazil some 500 years ago, with the original goal of producing sugar for domestic consumption and export. Technology transfer was key to the crop's development from the very beginning, and imported cultivars were transferred widely both within mills and throughout Brazil. Until as recently as 1980, all of the main varieties originated from other countries: in the central-south, for example, the most common variety was NA56-79 from northern Argentina.

During the 1980s and 90s, Brazilian agronomists brought in a wide range of technologies from abroad and adapted them for local use. At Copersucar, a major private cooperative of mills in Brazil, the main sources were the South African Sugar Technologists' Association (SASTA) and Texas A&M University in the United States. These institutions were crucial to the developments that took place in Brazil, primarily in the areas of agronomy and agricultural engineering.

The work of the Agronomic Institute of Campinas (IAC) and the research and educational services of the University of São Paulo's Agricultural School Luiz de Queiroz (ESALQ) were also important in the agronomy of sugar cane production. The scientific base provided by these institutions established a knowledge platform from which to absorb previously transferred technologies and to move to the next stage of technology transfer, driven by the emergence of Proálcool.

16.6.1 Proálcool's Emergence Leads to Genetic Improvements

The emergence of Proálcool in the 1970s drove two large varietal improvement programs that, from 1980 on, led to the annual penetration of new Brazilian sugar cane varieties that surpassed earlier imports. One of these programs, run by Copersucar through its research center, CTC, focused on the needs of sugar cane cultivation in São Paulo (SP varieties). The other program, Planalsucar (RB varieties), was carried out at experimentation stations of the government's Institute of Sugar and Alcohol (IAA) and was aimed at the northeastern and southern regions. As a result, there are now no imported commercial sugar cane varieties in use in Brazil, as they would not match the quality of domestic cultivars. Imported varieties are used only as potential progenitors for crossbreeding programs.

The penetration of Brazilian varieties was a key factor in the technological leap in sugar cane cultivation in Brazil. The original germplasm bank was all imported; but the use of transferred technologies to improve these cultivars, including selection and improvement techniques, was crucial. During the 1970s and 1980s, the Hawaiian Sugar Cane Planters Association provided planning support to Copersucar's varietal improvement program. Copersucar also exchanged information on a regular basis with the Bureau of Sugar Experiment Stations (BSES) in Australia and with U.S. programs. For example, all the main cultivars of the germplasm bank of Canal Point, Florida, were transferred to Copersucar. As part of the transfer process, workshops were developed with the specific objective of evaluating the Copersucar program, engaging research groups from Australia, South Africa, and the United States.

With regard to genetic changes, Brazilian researchers, trained in basic techniques in the United States, implemented the Brazilian genetic improvement program, initially at Copersucar. Copersucar also led an international consortium of groups from Australia, South Africa, the United States, and other countries. In Brazil, these developments led, for the first time ever, to the genetic mapping of the sugar cane plant in 2001. This effort was financed by the Research Support Foundation of the State of São Paulo (FAPESP), among others.

Today, Brazil is home to more than 500 transformed sugar cane varieties not yet in commercial use. Roughly 80 percent of the country's sugar cane fields are planted with up to 20 of these varieties, according to the São Paulo Association of Sugar and Alcohol Manufacturers (UNICA). Today, this program engages many industrial and university partners and promotes intensive exchanges among them.

16.6.2 Foreign and Domestic Technology Transfer

Over the years, Brazil's sugar factories improved their technology through the use of imported equipment as well as by taking advantage of the smaller, incremental adaptations of Brazilian developers. The local capital goods industry also added to improved knowledge on key processes and equipment.

An interesting example of technology transfer within Brazil, established in the 1980s and still ongoing, is the Center for Absorption and Transfer of Technology (NATT) in the northeastern state of Alagoas. As Copersucar's CTC research center expanded the scope of its work in response to the needs of central-south Brazil, a group of Alagoas sugarcane producers created NATT primarily (but not exclusively) to absorb CTC technology and transfer it to Alagoas mills.

Since the launch of Proálcool in 1975, relevant stakeholders in Brazil have sought to obtain knowledge to increase the productivity of the sugar cane economy—about everything from the sugar cane plant itself to ethanol making and end uses. In the late 1970s, with financial support from the Research Financing Foundation of Banco do Brazil (FIPEC), Copersucar sent a dozen Brazilians to Mauritius for one year to learn sugar and ethanol production. Upon their return, this group became the core of CTC's industrial unit in the 1980s. The integration of this group with CTC agricultural groups, adopting the biorefinery approach, was a key factor in CTC's success.

CTC's industrial unit contributed substantially to the absorption of foreign technologies via contracts with foreign and Brazilian companies, consultants, research centers, and universities. In the area of ethanol fermentation, for instance, extensive work on yeasts, biocides, and fermentation protocols was carried out with the Tropical Foundation of Technological Research André Tosello (FTPT) in São Paulo and with the Gulbenkian Foundation of Portugal. Training took place in the laboratories of the Centre National de la Recherche Scientifique (CNRS) in Toulouse, France. Consulting support was obtained from UNDGA, and research on the optimization of distillation systems was done in France. Other projects included consulting with Karlshue University in the area of infection-free fermentation and contracts with the German Research Centre for Biotechnology (GBF) in Braunschweig on new product fermentation.

16.6.3 Capital Goods Technologies

Brazil's sugar and ethanol capital goods industries incorporated knowledge from a variety of origins to develop equipment and machinery in all areas of sugar cane transformation, from sugar and ethanol production, to electricity generation, to milling. Sugar cane juice extraction technology, for instance, benefited substantially from foreign inputs, though this was always adapted in some critical way that made the resulting Brazilian version superior to the imported one. This process started with the migration of a group of South African consultants to Brazil in the late 1970s, which led to development of the Brazilian roller mill, and was later continued in the 1980s with the support of Australian consultants.

The technology for dehydrating hydrous ethanol, too, has evolved significantly in Brazil, progressing from a process of azeotropic distillation using benzene, to the use of cyclo-hexane, to the use of molecular sieves and ethylene glycol dehydration. In each case, Brazil's capital goods industry transferred and adapted new technologies to serve the Brazilian and export markets. Technologies brought in directly by the foreign capital goods industry (established in Brazil) also played a role in these developments.

16.6.4 End-Use Technologies

At the same time that technological developments were taking place in the agriculture and conversion stages of ethanol production, Brazil was developing and transferring end-use technologies as well. The Air Force Technology Center (CTA) and the country's private automobile industry developed new technologies that enabled the efficient use of ethanol in gasoline blends, hydrous ethanol, and more recently blends of any composition of hydrous ethanol and gasoline (actually a 25-percent ethanol blend by volume) in the country's new flexible-fuel vehicles (FFVs).

With support from CTA, Brazil's auto industry was able to successfully adapt the existing spark-ignition engine technology to use ethanol-gasoline blends. The partnership also led to development of the hydrous ("neat") ethanol engine technology in Brazil. This required developing an engine with a higher compression ratio to extract maximum benefit from the higher octane rating of ethanol compared to gasoline. (See Chapter 15.)

Flexible fuel engine technology was first developed in the United States and the Netherlands, and is based on the use of sensors that recognize the oxygen content of the fuel and trigger automatic adjustments in the air-to-fuel ratio. In the United States and Europe, this led to development of the so-called E85 FFV engine, optimized to a blend containing 85 percent anhydrous ethanol and 15 percent gasoline. Unfortunately, due to a lack of infrastructure to distribute and store this E85 fuel, most of the 5 million or so E85 vehicles in the United States and Canada run on gasoline instead. In Europe, the E85 engine has made limited inroads in the Swedish market and is being proposed for other markets.

Brazil's FFV technology, in contrast, relies on sensors derived from Italian, German, and U.S. technologies and can use any blend of hydrous ethanol and gasoline (actually a 25-percent ethanol blend by volume). Since every gas station in Brazil has at least one pump dispensing hydrous ethanol (thanks to prior government initiatives), there is no infrastructure constraint to market growth of Brazilian FFVs. In fact, the Brazilian market has responded so favorably to this new technology, which was adapted by the auto industry to Brazilian conditions, that today more than 70 percent of the incremental auto output in the country is comprised of FFVs. The downside of this success is that the fuel consumption per vehicle is not optimized for the varied compositions of the blend that the consumer makes when filling up at gas stations. As a result, excessive fuel consumption is taxing the hydrous domestic ethanol supply and limiting the prospects for exports.

16.6.5 Infrastructure Technologies

Brazilian mills and distilleries, as well as the oil company Petrobras, played a key role in developing the storage and distribution infrastructure for ethanol throughout the country. With the drive for ethanol exports, mills and distilleries invested in expanding the storage and loading capacities at ports such as Santos, Paranaguá, and Maceió.

Petrobras and other oil distributors in Brazil developed and transferred blending technologies to enable the distribution, storage, and use of ethanol-gasoline blends with up to 25-percent ethanol content. Petrobras also had to invest in technological developments to transport ethanol in pipelines, due to the presence of water in pipeline systems. Brazil is the only country in the world that uses gasoline and other clear-product pipelines to move ethanol. (See Chapter 14.)

16.6.6 Environmental Technologies

Many developments have helped to promote the environmental sustainability of Brazil's ethanol economy. With respect to air quality, government policies favored ethanol because of the fuel's high octane value, which eliminated the need to use the pollutant tetra-ethyl lead (TEL). Brazil was one of the first countries in the world to completely phase out TEL, in the early 1990s. This same substitution approach could be transferred to other countries that still use TEL, as well as to the aviation industry, which obtains its high octane from TEL.

In the agricultural arena, the technology of harvesting sugar cane without engaging in prior field burning, now being adopted on a large scale in the state of São Paulo, could be transferred to elsewhere in Brazil as well as to other countries still using this practice. The practice of returning vinasse (the large-volume liquid residue from sugar cane processing) to the fields as a combined source of fertilizer and irrigation water could also be transferred.

Studies of the carbon-recycling capacity of sugar cane-based ethanol have demonstrated that, compared to gasoline, fuel ethanol contributes substantially fewer greenhouse gas emissions.

(See Chapter 11.) The major reason for this is that bagasse is the only fuel required to convert sugar cane into products and into surplus electricity that can be sold to the grid. (In contrast, fuel ethanol made from corn in the United States and from sugar beets and wheat in Europe resorts to fossil fuels to provide the required process energy.) There are still many sugar cane-based operations in the world that could benefit from the transfer of Brazilian bagasse utilization technology.

16.6.7 Government Policies and International Cooperation

Governmental policies—translated into legislation and regulations—have provided an important enabling environment for investments in ethanol production in Brazil. Over the years, policy tools have ranged from direct subsidies to mandates making the use of anhydrous ethanol blends mandatory (by specifying gasoline as an ethanol-containing blend). The use of government banks to finance the development of sugar cane and ethanol production was also crucial to the success of the Proálcool program and provided a level of comfort for investment to take place. (On the international level, the World Bank extended financing to Proálcool in the late 1970s and again in the early 1980s, with part of the loan earmarked for technology development and transfer.)

Proálcool drove technology transfer and change as the ethanol industry moved from meeting the needs of the beverage and industrial markets to satisfying Brazil's growing demand for transportation fuels—a much larger and more competitive market that required new technologies. These technological developments have played a vital role in lowering the costs of ethanol production in Brazil and making it competitive with gasoline any time the price of crude is higher than €25–29 ($30–35) per barrel.[8]

As a result of Brazil's successful implementation of Proálcool, other countries have become interested in learning from this experience and engaging in bilateral cooperation. Brazil has signed memoranda of understanding on technology transfer with countries in Central America as well as with China, the Dominican Republic, Haiti, India, Nigeria, Thailand, and Venezuela. In some countries, Brazilian ethanol is being imported to develop domestic markets while local production ramps up.

16.7 Conclusion

Because technology is typically more than just a piece of hardware or a set of ideas, it is not always easy to replicate another country's experience with technological change and transfer. One of the sources of Brazil's biofuel success, for example, has been the country's strong foundation of research, education, and training, a capacity platform that required sustained effort over time to establish and maintain. This situation may not be easily found in other countries (particularly developing countries), though it does point to policy initiatives that they could consider. The willingness of Brazil's private sector to bring in technology from abroad and adapt it to local conditions was critical to the development of Proálcool. The ability to then resell the imported technologies, with added adaptations and improvements, reflects the existence of a strong capacity platform.

Countries with the elements of such a system of innovation in place will be able to move more rapidly along the biofuel pathway. This includes, among other things, having well-developed research, education and training, standards and norms, quality control, engine repair services financing, venture capital, marketing, capital goods industries, openness to technology transfer, and foreign investment and trade. However, even if a country's system of technological innovation is well developed, variations in climate, water availability, and agricultural potential could still hamper replication.

One way Brazil (and other biofuel leaders) can stimulate biofuel technology transfer abroad is through bilateral technological cooperation, supported by government diplomacy and implemented by the private sector. A basic requirement for developing a sustainable *international* market for a biofuel is the promotion of sustainable *domestic* markets in countries where it makes sense. Thus, Brazil has promoted bilateral cooperation on ethanol—through memoranda of understanding—with China, Colombia, Central America, the Dominican Republic, Haiti, India, Thailand, and Venezuela, among others.

As Brazil's experience demonstrates, the transition to a bio-based energy future offers plenty of strategic opportunities for private, public, and multilateral capital to finance development, not to mention carbon recycling.[9] Any country interested in biofuel development would do well to consider the strategic approach suggested in Figure 16–2 of this chapter and to decide through the interactions of relevant stakeholders on the best way to move forward and manage technological change and transfer.

PART VI. THE POLICY FRAMEWORK

Chapter 17. Biofuel Policies Around the World

17.1 Introduction

Policy instruments are vital to the development of strong biofuel industries. If governments and others wish to significantly expand production and use of these fuels at the domestic and global levels, they will need to have an effective "toolbox" of wide-ranging policy strategies. The most common policies supporting biofuels today are blending mandates and exemptions from fuel taxes. Other policy instruments have included loan guarantees; tax incentives for agriculture and forestry, consumers and manufacturers; preferential government purchasing policies; and research, development and demonstration funding for current and next-generation biofuels and technologies.[1]

Although governments adopt biofuel policies for a variety of reasons, the main driver to date has been to advance economic development in rural areas and create jobs. Subsidies for these fuels have been justified as indirect aid to domestic agriculture, and farmers increasingly recognize the market potential of energy crops as added sources of income. In parallel, governments have been motivated by a desire to reduce dependence on foreign oil and minimize the associated security and economic costs. Governments that have ratified the Kyoto Protocol are also promoting biofuels as a way to meet national or regional greenhouse-gas (GHG) emissions reductions targets, as the transportation sector accounts for a growing share of energy-related emissions linked to global climate change (approximately 25 percent today).[2]

As awareness of the potential of advanced biofuels grows, new policy instruments are emerging to facilitate their market development. Research investments sponsored by the U.S. Department of Energy, for example, recently led to a 30-fold reduction in the cost of producing enzymes used in cellulosic ethanol production, a major advance toward commercializing this technology. Researchers in several countries are also working on "co-product" development, using bio-based resources to produce biofuels as well as additional marketable products. And many countries are moving toward more-sustainable approaches in their biomass planning processes, including Brazil's gradual phase-out of burning in sugar cane harvesting and Malaysia's development of "Sustainable Palm Oil Principles" in response to environmental concerns about palm oil production.[3]

It is clear from existing experience that the policies governments adopt, and the specific ways these policies are designed and implemented, will be critical to how the biofuel industry develops and what impacts (positive or negative) it will have. This chapter describes the range of policies that have been used to date to promote biofuels at the national and international levels. The emphasis of the chapter is on market creation, with a brief analysis of which policies have been most effective thus far. Further discussion of specific types of policies, including quality and sustainability standards and certification systems, are found in other chapters and in the final recommendations of this report.

17.2 Regional, National, and Local Policies

Several regions and countries have implemented targets, policies, standards, and action plans that aim to boost biofuel production and consumption substantially in the coming decade. Table 17–1 highlights selected national, regional, and state fuel-blending targets and mandates for ethanol and biodiesel.[4] Greater detail on these programs in specific regions or countries is provided later in this chapter.

Table 17–1. Selected Regional, National, and State Biofuel Mandates or Targets

Country or Region	Fuel	Mandates or Targets
Australia	Biofuel	350 million liters by 2010
Brazil	Biodiesel	2% of diesel by 2008; 5% by 2013
	Ethanol[a]	20–25% of all gasoline (current)
Canada		
Ontario	Ethanol	5% of gasoline by 2007
Saskatchewan	Ethanol	7% of gasoline as of April 2005
China		
National	Ethanol (corn)	2.5% of gasoline by end of 2005[b]
Jilin	Ethanol (corn)	10% of gasoline from October 2005
Colombia	Ethanol	10% in all cities of more than 500,000 people
European Union	Biofuels	2% of motor fuel by 2005[c]; 5.75% by 2010 (targets)
Austria	Biofuels	2.5% of all motor fuel by October 2005; 5.75% by October 2008
France	Biofuels	7% of motor fuel by 2010; 10% by 2015
Germany	Biofuels	2% of gasoline from 2007 to 2009
	Biodiesel	4.4% of conventional diesel, from 2007
Sweden	Biofuels	Eliminate use of fossil fuels 100% by 2020
India	Ethanol	10% ethanol blending (E10) in 9 of 28 states and 4 of 7 federal territories (all sugar cane-producing areas) starting in 2003[d]
	Biodiesel	5% of diesel fuels, no set date
Japan	Biofuels (or gas-to-liquid fuels)	20% by 2030 (target)

Malaysia	Biodiesel (palm oil)	5% of diesel by 2008
Philippines	Biodiesel (coconut methyl ester-CME)	1% CME for all government vehicles (began in 2004); 1–5% of diesel from CME biodiesel blends 2006–2014
Thailand	Ethanol	10% gasoline blend to replace conventional gasoline by 2007
	Biofuels	10% of all motor fuel by 2012
United States		
National	Ethanol	28 billion liters (7.5 gallons) of ethanol to be produced by 2012
Hawaii	Ethanol	At least 85% of gasoline must contain 10% ethanol by April 2006
Minnesota	Ethanol	20% of gasoline by 2013 (up from current 10%)
	Biodiesel	2% of diesel as of October 2005
Montana	Ethanol	10% of gasoline

Notes: (a) here, ethanol feedstock is sugar cane unless otherwise noted; (b) Chinese provinces have had to suspend blending mandates due to ethanol shortages; (c) This target applies to all member states of the European Union. However, member states may choose targets that go further than the European target. The actual share achieved as of February 2006 is approximately 1.4 percent; (d) due to poor cane crop yields during 2003–2004, India had to import ethanol in order to meet state blending targets, and has had to postpone broader targets until sufficient supplies of domestic ethanol reappear on the market.
Source: See Endnote 4 for this chapter.

17.2.1 Africa

Several African countries currently have biofuel policies in place, some of which date back to the 1970s (shortly after Brazil began its Proálcool program). Three of the first three countries to experiment with ethanol, Kenya, Malawi, and Zimbabwe, have had very different experiences with developing the fuel. South Africa and a handful of other African countries are also expanding biofuel efforts.

Malawi is the only country outside of Brazil that has been blending ethanol continuously on a national basis for more than 20 years.[5] The price of the fuel has been pegged to gasoline, with an incentive of 5 percent or more, depending on the volume of ethanol blended.[6] Zimbabwe, in contrast, initially used a cost-plus basis formula, offering the national oil company a 5 percent incentive over the cost of ethanol production, though later the price of ethanol was pegged to the price of gasoline. Periodic droughts caused Zimbabwe to halt its blending in the early 1990s.[7] Kenya had a single distillery that produced ethanol from molasses in the 1980s, providing fuel to Nairobi, but it suffered setbacks due to low government-controlled retail prices, inadequate plant maintenance and operation, resistance from local subsidiaries of multinational oil companies, and, unfavorable exchange rates.[8]

In South Africa, where the SASOL company is a leading producer of synthetic ethanol from coal, there is now movement toward ethanol production from crops.[9] In 2006, a biofuel pilot project was under development in the Eastern Cape.[10] The South African government has developed a national biodiesel standard, based on the EU standard EN 14214, and is expected to enact a fuel blending mandate (1–3 percent biodiesel) by the end of 2006.[11]

Several other countries across Africa have enacted (or are in the process of enacting) initiatives to expand the production and use of biofuels, including Ghana, Ethiopia, and Benin.[12] A few African countries, including South Africa and the Democratic Republic of Congo, currently export ethanol to the EU under the General System of Preferences (GSP) and Everything but Arms (EBA) agreements. (See Chapter 9.) It is possible that future policies will be designed to meet not only domestic needs but also the growing international demand for biofuels produced in Africa.

17.2.2 Asia and the Pacific

Rapid population and economic growth in Asia and the Pacific are resulting in higher energy demand. To meet rising transport fuel needs, several countries in the region are implementing policies to accelerate biofuel expansion. China, for example, has promoted ethanol on a pilot basis since 2001 in five cities in its central and northeastern regions—Zhengzhou, Luoyang, and Nanyang in Henan province, and Harbin and Zhaodong in Heilongjiang province.[13] The country's Renewable Energy Law, endorsed in February 2005, lays out a biofuel policy framework that increases biofuel targets from the present level of 3 percent of renewable energy to 10 percent by 2020.[14] The province of Jilin, home to the world's largest corn ethanol distillery, offers tax breaks, low-interest loans, and subsidies to compensate for the price differential between gasoline and ethanol.[15] Jilin's Tianhe distillery is producing more than 900 million liters (240 million gallons) of ethanol annually, operating only at about 75 percent capacity.[16]

India's government developed a Draft National Biofuel Policy to promote biofuels in 2003.[17] The national government has mandated the use of E5 in nine states since 2003 and enacted an excise duty exemption for ethanol; however, due to droughts and crop failures, it has been unable to keep pace with the mandate using domestically produced ethanol.[18] In addition, the Indian National Bank for Agriculture and Rural Development has provided refinancing (at 100 percent) to banks at a concessional interest rate for development of wasteland, helping non-governmental organizations (NGOs) and research organizations spread awareness about biofuels through demonstration projects and supporting state government initiatives to cultivate biodiesel crops such as pongamia.[19] India has significant potential for producing biodiesel from jatropha and is working to expand its production and use of biofuels, particularly in the poorest areas.[20] (See Chapter 2.)

Elsewhere in Asia, Thailand's government announced in May 2005 that it plans to spend €16.5 billion ($20 billion) over the next four years on energy and conservation programs. The government also plans to phase out the gasoline additive methyl tertiary-butyl ether (MTBE, which currently comprises 10 percent of gasoline blends), and to replace it with ethanol.[21] In the Philippines, government vehicles are required to use a 1 percent biodiesel blend, and the government is deliberating the passage of a 1 percent national biodiesel requirement that will increase to 5 percent.[22] Ethanol is also mandated under the National Bioethanol Program, starting with the use of five percent blends in gasoline from 2007–2010 and 10 percent blends from 2010–2017; this is scheduled to displace a total of 3.7 billion liters of gasoline over a 10-year period.[23]

Japan has set an ambitious goal of replacing 20 percent of its oil demand with biofuels or gas-to-liquid (GTL) fuels by 2030.[24] In the nearer term, Japan has proposed a target of 500,000 million liters **(**132 million gallons), or about 1 percent of projected fuel use, by 2010. To facilitate market development of ethanol, the government proposed an E3 standard in 2004 as a lead-in to a national E10 blend standard by 2010 (this standard may be substituted with ETBE blending).[25]

Australia's government has supported ethanol since 2000 with a variety of tax incentives and production subsidies.[26] The Australian biofuel industry is provided a lower excise rate than petroleum fuels, a production subsidy for domestic biofuels, and capital grants to help cover the investment costs for new production facilities.[27] In addition, the government has established a target to increase production and use of biofuels to 350 million liters by 2010, a level that might well be surpassed under a new action plan. As of early 2006, more than 400 service stations around the country were selling ethanol and biodiesel blends.[28]

17.2.3 European Union

The European Union (EU) has had a regulatory framework in place to promote biofuels since the early 1990s. For example, the Common Agricultural Policy (CAP) included production quotas for oilseed food crops (the so-called Blair House Agreement) for EU member states, as well as exemptions from certain taxes, and explicitly granted permission to grow non-food crops on set-aside lands. In 2003, the EU issued a directive stating that all member states should set national targets for the use of biofuels in the transport sector of 2 percent by 2005, and 5.75 percent by 2010.[29] As a result, most member states have developed national biofuel plans, and several are providing substantial tax relief to promote biofuel production, as a result of the Transportation Fuels Fiscal Directive of 2003.[30]

This Directive provides certain fuel tax exemptions for biofuels to enhance their market competitiveness. For example, Sweden and Spain grant 100-percent tax relief for biofuels.[31] However, this varies greatly in other EU countries, creating the need for greater harmonization of energy tax laws within the EU to facilitate the development of alternative fuels.[32]

Despite these efforts, it has appeared unlikely that the EU targets for 2010 would be met under the 2003 policy framework—the EU market share for biofuels was expected to reach only 1.4 percent by the end of 2005, unless international trade is facilitated.[33]

In December 2005, the European Commission (EC) issued a Biomass Action Plan that sets out measures to promote biomass for transportation, heating, and electricity through cross-cutting policies that address supply, financing, and research. The plan concentrates on balancing domestic production and imports, using ethanol to lower fuel demand, and reducing technical barriers. It states the EC's intention to propose a strategy with an integrated approach to reducing carbon dioxide (CO_2) emissions associated with the transport sector, including the use of biofuels, fiscal incentives, congestion avoidance, consumer information, and improvements in vehicle technology.[34] It also proposes to amend EU standard EN 14214 to facilitate the use of a wider range of vegetable oils as biodiesel feedstock, and to ensure that only biofuels "whose cultivation complies with minimum sustainability standards count towards [EU biofuels] targets."[35] In addition, the plan discusses the need to maintain current preferential market access for developing nations, acknowledges sugar reforms and the need to help developing countries to advance their biofuel markets, and mentions the need to keep these objectives at the forefront of considerations during bilateral and multilateral trade negotiations.[36]

In February 2006, the Commission adopted a new and ambitious "EU Strategy for Biofuels," which builds on the Biomass Action Plan, to boost production and use of biofuels. It sets out three primary goals: "to promote biofuels in both the EU and developing countries; to prepare for large-scale use of biofuels by improving their cost-competitiveness and increasing research into 'second generation' fuels; [and] to support developing countries where biofuel production could stimulate sustainable economic growth."[37] Key policy tools will include stimulating demand, possibly through biofuel obligations, examining how biofuels can best contribute to greenhouse gas emissions targets, and directing research money toward developing the biorefinery concept and next-generation biofuels.

In addition to regional level policies, several European countries have national programs to promote biofuels. Austria has established mandatory targets for these fuels combined with tax exemptions, while France has enacted a tendering process that sets a maximum amount of biofuels for the market, with tax reductions for this amount of fuel.[38] Slovenia, the Czech Republic, and the Netherlands reportedly have plans to introduce obligations in the 2006–2007 timeframe, as does Germany.[39] And the United Kingdom is considering a trading system for biofuel certificates, as well as a blending obligation and certification system.

17.2.4 Latin America

Latin America is experiencing tremendous biofuels growth, following the leadership of Brazil in this area. Brazil's success stems from a combination of policies enacted over the years, beginning with the Proálcool program launched in 1975 to reduce dependence on imported oil. A combination of tax breaks and blending mandates drove investment in ethanol production and use and brought about rapid progress in the nation's ethanol industry. Subsidies to increase sugar production and distillery construction, along with government promotion of all-ethanol cars and development of a distribution infrastructure, also helped fuel development.[40]

In recent years, Brazil has begun to focus on biodiesel production and use as well. The government has mandated the use of 2 percent biodiesel by 2008, and 5 percent by 2013.[41] In 2004, Brazil issued an Executive Order and law encouraging biodiesel producers to buy feedstock from family farmers; the following year, it passed a law that, among other things, exempts from taxes any biodiesel produced by family farms.[42] The oil company Petrobras has begun tendering for biodiesel, facilitating development of the market.

Brazil has a National Agri-Energy Plan that addresses fuel ethanol, biodiesel, agri-forestry residues, and cultivated energy forests.[43] In addition, to facilitate the development of a diverse international biofuels trade, Brazil recently signed multiple memoranda of understanding (MOUs) with the governments of Nigeria, Japan, Venezuela, China, and India—as well as with private entities in these nations. These MOUs are intended to create frameworks for countries to share technology and to help the latter countries develop, market, and trade ethanol-related technologies and expertise. Brazil's aims are twofold: to increase demand for Brazilian biofuels around the world, and to help guarantee reliability of supply in the global marketplace, enhancing private sector development. For instance, if a drought resulted in lower production levels in Brazil, other countries such as South Africa and India could still supply the market, and vice versa.

Other countries in Latin America have begun to enact biofuel incentives as well. An ethanol-blending mandate is now in force in some regions of Venezuela, and the government is considering enacting a 10-percent national blending requirement.[44] Colombia currently requires a 10 percent ethanol blend in cities with more than 500,000 people.[45] Several other countries in the region also have biofuel initiatives, including Argentina, Mexico, Paraguay, and Peru.

17.2.5 North America

Like Brazil, the United States first began to seriously promote ethanol in response to the oil crises in the 1970s, primarily through tax policies. More recently, the Farm Security and Rural Investment Act of 2002 (the "Farm Bill"[*]) contains an energy title designed to promote energy efficiency and the development of clean energy from alternative resources that can be produced by the agricultural sector, including biofuels. The title authorizes support for biofuels through a variety of programs, including biorefinery development grants, biomass R&D, and federal procurement requirements for bio-based products. However, funding for these programs has been inconsistent, and several programs have received reduced funding or none at all. Planning is now under way for a new five-year Farm Bill for 2007, and it remains to be seen whether the government will support such programs with concrete funding commitments.

Most U.S. federal biofuel incentives to date have focused on ethanol. However, the nation's first federal biodiesel tax incentive was enacted as part of the American Jobs Creation Act (Jobs Bill) of 2004, to help reduce the price of biodiesel for consumers. (The 2004 Jobs Bill also applies to ethanol, extending federal tax credits through 2010 and expanding the flexibility of these credits so they apply to any ethanol blend fraction up to 10 percent.[46†]) Biodiesel use is also being promoted in the military: as of June 2005, the U.S. Navy and Marine Corps were required to operate non-tactical diesel vehicles on a 20 percent (B20) biodiesel blend.[47]

In 2005, the U.S. government enacted a new Energy Policy Act (EPAct), the first major energy law adopted in 13 years. It includes several incentives to spur expansion of a biofuel market, including a Renewable Fuels Standard (RFS) that requires the production of 28 billion liters of ethanol by 2012, tax incentives for E85 fueling stations, biofuels tax and performance incentives, and authorizations for loan guarantees, a bioenergy R&D program, and biorefinery demonstration projects.[48]

In addition to these national provisions, a growing number of U.S. states are enacting policies to encourage market expansion of biofuels, including RFS laws and tax incentives. North Dakota, for example, committed in 2005 to providing up to $4.6 million (€3.8 million) over two years to facilitate ethanol production, creating a tax incentive for consumers who purchase E85 gasoline, establishing an investment tax credit for ethanol and biodiesel production facilities, and offering income tax credits and other benefits for biodiesel.[49] In the fall of 2005, New York state launched a Strategic Energy Action Plan that includes tax credits up to $10,000 (€ 8,265) for alternatively fueled vehicles, depending on vehicle weight.[50] And in early 2006, New York Governor George Pataki announced an initiative to make renewable fuels tax-free and available at service stations throughout the state.[51] Minnesota has enacted the most ambitious mandates

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[*] Agriculture policy takes shape in the so-called "farm bill," which is re-authorized approximately every five years. The Farm Bill contains federal commodity support programs, land conservation, forestry programs, rural development, hunger/nutrition programs for underprivileged people, as well as a clean energy title.
[†] Under earlier laws, tax credits were geared toward blends of 5.7 percent, 7.7 percent, and 10 percent, per terms of obsolete requirements under the Clean Air Act.

in the United States thus far, calling for ethanol to represent 20 percent of gasoline by 2013; it also requires a 2 percent biodiesel blend. As of early 2006, new initiatives were under way in several other states and at the federal level as well.

Several provinces in Canada are also promoting the production and use of ethanol through subsidies, tax breaks and blending mandates. Ontario, for example, has enacted a renewable fuels standard of 5 percent ethanol beginning in January 2007. Manitoba and Saskatchewan have also mandated the blending of ethanol into gasoline.[52] At the national level, Canada aims to replace 35 percent of its gasoline with E10 blends by 2010 in order to meet commitments under the Kyoto Protocol; this would require the production of 1.2 billion liters (350 million gallons) of ethanol.[53]

17.3 Policy Lessons to Date and Remaining Barriers

The modern biofuel industry is still relatively young, with little long-term policy experience. Brazil, the United States and Malawi have the longest record of support for biofuels, and the experiences in these countries and elsewhere provide valuable lessons on ways to support the nascent industry. It is also important to address remaining barriers—whether policy or institutional—that slow the advancement of biofuels.

Research and development are critical to the success of biofuels, but, as with other renewable fuels and technologies, market creation is the most important force for driving their production and use. There is no example in the world of a country that has established a biofuel market without the use of mandates and/or subsidies, and the combination of these two policy tools has been most effective. But a comprehensive approach to market development is essential. Thus, it is also important to enact policies that develop the necessary infrastructure for production and distribution.

17.3.1 Lessons from Brazil

Brazil is a case in point. After Brazil's Proálcool program was enacted in the 1970s, the nation's ethanol industry made rapid progress, spurred by a combination of blending mandates and tax incentives that drove investment in the production and use of ethanol. The Brazilian government also promoted the manufacture and sale of "neat" (pure) ethanol cars and provided subsidies to increase sugar production and distillery construction. In addition, infrastructure was developed to distribute neat ethanol to virtually all pumping stations around the country. Largely as a result of these policies that created demand and provided access to the marketplace, the ethanol industry grew quickly, such that neat ethanol-fueled vehicles represented 96 percent of total car sales by the mid-1980s.[54]

But falling oil prices and rising sugar prices in the mid- to late-1980s and 1990s provided oil companies an opportunity to take back a large share of the market lost to ethanol, and ethanol growth slowed dramatically. From 2003, the ethanol and auto industries promoted the production of flexible-fuel vehicles (FFVs) that can run on virtually any mixture of gasoline and ethanol.[55*] As a result, the market was changed almost overnight as Brazilian drivers no longer

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[*] The Brazilian government required that all new vehicles be able to run on up to 25 percent ethanol. Also government subsidies and tax breaks to develop technology and government-funded research helped the

needed to worry about price or supply fluctuations, but can change their consumption decisions even faster than producers can adjust.[56]

While the ethanol industry in Brazil began with a host of subsidies, none of these remain in place today, excepting the fact that biofuels are subject to lower taxes and that there exists a 20–25 percent ethanol blending mandate in all gasoline. In addition, at the end of 2005, neat ethanol sold for nearly 40 percent less than the gasoline/ethanol blend, even accounting for the lower energy content of ethanol.[57]

17.3.2 Lessons from the United States

While biofuels supply a far smaller share of total fuel in the United States than in Brazil, U.S. production has expanded steadily in recent years. Ethanol production in particular has been spurred primarily by state and federal incentives, stricter environmental legislation (most notably the Clean Air Act of 1990), falling production costs, and rising demand. In its early years, however, the biofuels market and industry grew far more slowly in the United States than in Brazil. This is likely explained, in great part, by the fact that there were no production or blending mandates in the United States until recently.

Although it remains to be seen if the U.S. production mandate will prove successful (and we may never really know because many experts predict the market to expand beyond the mandated production level by 2010, regardless of federal law), it seems logical that blending mandates are generally preferable. Blending mandates create a market for biofuels—rather than requiring specific production levels—while also indirectly requiring that an infrastructure be developed to get the product to that market.

Biodiesel production remains low relative to ethanol production and use in the United States, but it is growing rapidly. The U.S. military has recently become a significant demand driver for this fuel due to the requirement that all non-tactical military diesel vehicles use a 20-percent biodiesel blend. Because governments are generally the largest single users of energy within a country, government purchase requirements can play a major role in creating large and consistent markets for biofuels.

17.3.3 Lessons from Europe

Europe's experience with biofuels offers some important lessons as well. As mentioned earlier, the EU failed to meet its biofuel target of 2 percent of all gasoline and diesel for transport use by 2005 under the EU Biofuels Directive of 2003, and it will be unlikely to meet its target of 5.75 percent by 2010. In fact, as of early 2006, the Eurpean Commission was in the process of taking Slovakia, Luxembourg, Italy, and Portugal to the European Court of Justice for failing to actively contribute to biofuel development, and was considering replacing the EU target with a biofuel obligation.[58] Experience in Europe to date suggests that voluntary targets are hard to meet, at least when they are not supported with incentives to create a market and drive investment in the industry. Those countries in Europe that have seen the greatest success with biofuels—including Germany, Spain, France, and the Czech Republic—all have domestic supplies of first-generation feedstock (i.e. rapeseed in Germany, wheat in France and the Czech Republic, and grapes in France) as well as biofuel policies that support local farmers.

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auto industry develop the FFVs, equipped with special motors to switch between gasoline, ethanol, and natural gas.

It is also important that direct payments to support the biofuels industry gradually be reduced and then sunset when the biofuels in question become more financially viable, as they have in Brazil. Countries can follow the German example in the field of renewable energy (e.g. wind and solar power), phasing out subsidies according to the level of economic performance: once a market exceeds a predetermined level, incentives such as tax exemptions should end. Not only does this ensure that the public will not be subsidizing the industry in the very long term, but such policy design can also enable countries to encourage the development of next-generation technologies, which can continue to receive tax breaks or other incentives until they are cost-competitive.

17.3.4 Lessons from Asia

Policies promoting biofuels in Asia have also been instructive. Thailand has been extremely successful entering the biofuels market. Driven by a desire to reduce oil dependency and create jobs in rural areas, Thailand's 30-year-old biofuels program recently launched a €30 million ($25 million) "investment roadmap" to support the target of 8.5 million liters of biodiesel production by 2012. Also interested in producing ethanol to absorb surplus sugar cane and cassava, Thailand has launched incentive programs for those wanting to establish new plants, and Special Purpose Vehicle Schemes to encourage the vehicle production to be compatible with biofuels.

In India, where the government has put both biodiesel and ethanol blending requirements in place in certain states, the government seeks to replicate the success of the country's National Dairy Development Board. This model encourages the formation of farmer cooperatives that span a cluster of villages, where each farmer buys a share in the society in and sells his or her oilseeds through the cooperative in exchange for greater organization of financial capital, fertilizer, planting materials, and other inputs.[59]

17.3.5 Overall Policy Lessons and Remaining Barriers

Based on experiences to date, it is clear that long-term governmental and stakeholder commitments to biofuels are critical; that a combination of policies is needed to drive the market and development of necessary infrastructure, and that policies must be consistent and flexible enough to tackle new challenges as they arise. In addition, in order to address concerns about fuel quality, possible social and environmental costs, and other issues, these policies may be combined with standards and certification schemes. (See Chapter 18.)

It is also critical to eliminate or alter those policies that work against the production and use of biofuels. Despite the many initiatives worldwide to advance biofuels, there remain a number of policy or institutional barriers that cause market distortions and slow market entry for these fuels. Greater development of coal-to-liquid (CTL) fuels could also compete with biofuels and slow market growth. In general, petroleum subsidies tend to hinder or preclude new fuels from entering the market by making market penetration more difficult. (See Chapter 8.) China provides significant direct subsidies for oil, perhaps as much as $20 (€16.5) per barrel during times of high prices, though the actual impact on the economy is unclear.[60] Meanwhile, *indirect* subsidies, including the cost of defending oil supplies, to the U.S. oil industry have been estimated at roughly $111 billion (€92 billion) annually for light-vehicle petroleum fuels.[61] (See Chapter 7.)

For biofuel to play a greater role in the transport sector, the playing field must be leveled through the gradual elimination of subsidies for petroleum-based fuels. As the price of oil increases, biofuels will become more cost-competitive, making it easier for them to compete with conventional fuels. However, the same can be said for unconventional liquid fossil fuel resources such as tar sands, which could become a large part of the future energy mix if the price of oil is high enough and associated costs of land use, water, and other environmental resources are not taken into account. This real possibility highlights the importance of also incorporating external security, social, and environmental costs (climate change in particular) into the price of energy. (See Chapter 11.)

Other barriers that continue to exist on the domestic and international levels must be addressed as well. For example, if the oil industry controls the supply and distribution of biofuels, this may lead to price manipulation. Unreliable supply and demand for biofuels can create uncertainty and impede market development. A lack of environmental oversight can result in backlash if rapid biofuel expansion leads to unsustainable production practices. The lack of a global commodity market for biofuels may slow supply growth. And the absence of international standards and/or certification schemes creates uncertainty for equipment and technology suppliers and may impede international trade. (See Chapter 9.) Overcoming resource and production constraints requires policy and/or institutional reforms as well.

17.4 Relevant International Policy Instruments and Initiatives

At the 2002 United Nations World Summit on Sustainable Development in Johannesburg, South Africa, the Brazilian government proposed an Energy Initiative aimed at establishing targets and timetables for increasing the share of the world's energy derived from renewable sources. It proposed that by 2010, renewable energy sources represent 10 percent of world energy consumption, with new renewables (not including traditional biomass or large-scale hydropower) representing 5 percent of total energy use.[62] In response to Brazil's proposal, Latin America and the Caribbean agreed to a regional 10 percent target by 2010 for renewable resources.[63] While these initiatives do not include a specific share for biofuels, these fuels are an increasingly important option for meeting such targets. Several international initiatives also have been established to facilitate the global market expansion of biofuels specifically.[64] (See Table 17–2.)

Table 17–2. Selected International Biofuels Initiatives

Initiative and Sponsor	Year Launched	Purpose
Task 40: Sustainable International Bioenergy Trade, International Energy Agency (IEA)	2004	Focuses on Bioenergy Trade, particularly to develop "commodity markets" at the local, regional, and global levels to foster long-term sustainability and stability.
Sustainable Energy Finance Initiative, UN Environment Programme*	2004	Aims to encourage investments in sustainable energy through partnerships and to bring these energy resources into the mainstream.

* SEFI is a joint effort of the UNEP Finance Initiative, the UNEP Energy Branch, and the Basel Agency for Sustainable Energy, with support from the United Nations Foundation.

International Partnership on Bioenergy, led by the Italian Ministry for Forestry and Territory	Grew out of 2005 G-8 commitment to further develop biofuels for transport, heat, and power.	Aims to focus on alleviating barriers to bioenergy development, among other issues.
Biofuels Initiative, United Nations Conference on Trade and Development (UNCTAD)	June 2005	Will help poorest developing countries increase production, use, and trade of biofuel resources and technology in coordination with other groups.
International Bioenergy Programme, United Nations Food and Agriculture Organization (FAO)	To be launched in 2006.	Aims to promote biomass as a means to address poverty and climate change by facilitating partnerships and working to reconcile any "food versus fuel" issues that might arise.

Source: See Endnote 64 for this chapter.

While it is encouraging that these policies and programs are under way, there is a need for leadership to facilitate international policy developments and integrate disparate efforts related to biofuels. It is possible that the FAO or the IEA could play this role. UNCTAD is forming an International Advisory Expert Group for its Biofuels Initiative, and it has been suggested that the IEA Bioenergy Program's Task 40 could serve as an information clearinghouse, playing a coordination/facilitation role among various organizations, helping to design trading and other schemes, and perhaps developing projects.[65]

Well-functioning international capital markets will also facilitate development of a biofuel infrastructure.[66] Policies can be enacted to ensure that markets function properly, as well as to remove barriers. International financial institutions that direct development aid flows, such as the World Bank and Global Environment Facility (GEF), also play a role in market function. Their role in biofuel development is already beginning to grow, with new World Bank and Inter-American Development Bank biofuel projects being planned for the near term. [67] These institutions are eager to invest in biofuel projects able to simultaneously address poverty alleviation, climate change, and sustainable growth.

The GEF was designed to ensure that development projects are sustainable and provide incremental environmental benefits beyond what they would have without GEF assistance.[*] Already, it provides small grants to meet some of the objectives in its climate change "focal area" that will also help to promote biofuels. One existing program, for example, aims to reduce implementing costs and remove barriers for jatropha oil and rapeseed-derived biofuel in one or more developing countries.[68] One outgrowth of the GEF, the Sustainable Energy Finance Initiative (SEFI), aims to promote and support increased investment in energy efficiency and renewable energy by informing and connecting investors, creating a stable environment to

[*] The GEF consists of the UNDP, UNEP, and World Bank as its "Implementing Agencies" and Regional Development Banks as its "Executing Agencies."

catalyze investment flows, and minimize risk and uncertainty. SEFI has established guidelines for institutions and individuals interested in investing in renewable energy technologies, including biomass.[69]

17.5 Relevant International Environmental Instruments

A major driver behind rising in interest in biofuels is concern about global climate change, as well as the 2005 entry into force of the Kyoto Protocol. The European Commission, for example, is examining integrated ways that alternative fuels and vehicle technologies could help the EU achieve its carbon dioxide emissions-reduction targets under the international agreement.[70] Large developing countries such as China and India could soon become some of the largest emitters of greenhouse gases (GHGs), and biofuels provide an option for them to leapfrog to more sustainable fuels and technologies.

Significant opportunities continue to emerge for biofuel market expansion as countries look to address a number of goals, including domestic environmental and human health regulations, the creation of markets for energy crops as a new means for helping the domestic agricultural sector, and meeting international commitments on climate change.

17.5.1 Kyoto Protocol Flexible Mechanisms

There are two “flexible” financing provisions that provide opportunities to promote biofuel development under the Kyoto Protocol. The first is the Clean Development Mechanism (CDM), which grants “emissions reduction credits” for investments in emissions-reducing projects in developing countries.[71] The second is Joint Implementation (JI), which grants credits for projects in transition economies, such as those in Central or Eastern Europe. In order for projects to qualify for CDM or JI funding, they must achieve emissions reductions that are *additional* to any that would have occurred without the project.[*] For example, Brazil’s current ethanol program would not qualify for CDM funding, because it is well established. However, Brazil is proposing a new biodiesel project under the CDM that might qualify for additional reductions (excluding the share that is compulsory).

To date, there are few biofuel-related projects under consideration for the CDM or JI. This is because it is more difficult to determine baselines and measurement methodologies for biofuel projects than for other renewable energy or energy efficiency projects—in other words, it is difficult to determine to what extent biofuel projects will reduce GHG emissions below business-as-usual levels, particularly because lifecycle emissions vary according to feedstock and processing methods.[72] (See Chapter 11.) Furthermore, as with other CDM and JI projects, leakage (i.e., whether the project will result in higher emissions elsewhere) can be a problem with biofuel CDM and JI projects.[73] In spite of these challenges, CDM transportation projects are “in the pipeline” for Thailand (ethanol) and India (biodiesel and ethanol).[74]

The United Nations Conference on Trade and Development (UNCTAD) views the development of biofuels as a powerful poverty-reduction tool, and hopes to utilize the CDM to help mitigate

[*] Demonstrating this “additionality” has proven very difficult to accomplish at the methods and applications levels.

climate change through expanded production and use of biofuels. A UK-based group, Agrinergy, also recognizes the important role the CDM can play in promoting biofuels. This is particularly true for the near future (i.e. until cellulosic technologies become widely available) because the potential GHG emissions reductions from sugar cane-based ethanol can be significantly greater than those from grain-based ethanol, and ethanol production from sugar cane occurs primarily in tropical developing countries that can benefit from the CDM.[75] Agrinergy also recognizes the complexities associated with developing biofuel projects that could qualify for the CDM. Therefore, the firm is working to develop a CDM methodology for transport-related liquid biofuel projects, such that "only under clear and specific circumstances will biofuel use qualify as a CDM project."[76]

In addition, the 11th Conference of Parties (First Meeting of Parties) of the United Nations Framework Convention on Climate Change (UNFCCC), held in Montreal in December 2005, strengthened the CDM and expanded the scope to include policies and programs, not just single projects.[*] The latter is relevant for developing countries because it enables a cluster of activities to be registered under one Project Design Document, a step that will greatly reduce transaction costs.[77]

17.5.2 Carbon Finance Instruments and Developing Carbon Markets

The development of carbon finance instruments and carbon markets—for example, by the World Bank's Carbon Finance Unit (CFU), the Chicago Climate Exchange, and the European Union's Emissions Trading System (EU-ETS)—could create a market for carbon credits/emissions trading and facilitate biofuel market expansion as investors and countries seek to shift to low-carbon technologies and activities to reduce GHG emissions. The near-term efficacy of such instruments, the robustness of carbon markets, and the extent to which they will facilitate investments in sustainable, emissions-reducing projects—including in biofuels—remain unclear.

Initial forays into carbon finance have indicated that the price of carbon may be too low to spur the necessary behavior changes or investments in clean energy, and in this case, to facilitate more robust biofuel development. Another major issue will be how much carbon credit to give biofuels—and how to achieve agreed-upon metrics to reach such a determination.

The World Bank Carbon Finance Unit (CFU) uses funds contributed by companies and governments in industrialized nations to purchase project-based GHG emission reductions in developing countries and countries in transition. The emission reductions are purchased through one of the CFU's eight carbon funds on behalf of the contributor, and within the framework of the Kyoto Protocol's CDM or JI. The role of the Carbon Finance Unit is to catalyze a global carbon market that reduces transaction costs, supports sustainable development, and helps alleviate poverty and facilitate growth in the world's poorest nations.[78]

The Prototype Carbon Fund (PCF) was the first carbon financing mechanism at the World Bank. It is a public-private partnership consisting of 17 companies and six governments. It became operational in April 2000 with a mission of pioneering the market for project-based GHG

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[*] According to paragraph 20 on Further Guidance Relating to the CDM, "a local/regional/national policy or standard cannot be considered as a clean development mechanism project activity, but project activities under a programme of activities can be registered as a single clean development mechanism project activity."

emissions reductions, while promoting sustainable development and offering a "hands-on" educational opportunity to its stakeholders. As of early 2006, 21 projects had been funded through the PCF, and 7 more were under development.[79]

The selling of emission reductions—or carbon finance—has been shown to increase the bankability of projects by adding an additional hard currency revenue stream, which reduces the risks associated with lending. In this way, carbon finance provides a means of leveraging new private and public investments into projects that reduce GHG emissions, thereby mitigating climate change while contributing to sustainable development.[80]

17.6 Conclusion

Government-initiated policies, ushered in by key stakeholders, have been and will continue to be the main driver of the global biofuel industry. Biofuel subsidies have been justified as indirect aid to domestic agriculture, as a means of reducing dependence on foreign oil and its associated security and economic costs, improving local air quality, and, more recently, as a way to meet national or regional greenhouse gas emissions reductions targets. These goals will continue to be central, though the relative weight of these drivers may vary over time, and they require that future biofuel policies be designed to foster sustainable production for both industrial and developing countries.

For all countries, policies that guarantee demand and encourage technological innovation are essential. Blending mandates, government purchasing policies, and support of biofuel-compatible infrastructure and technologies have been most successful in developing a reliable market for biofuels in the countries and regions where they are being implemented. Other policies, such as loan guarantees, tax incentives for consumers and manufacturers, and direct industry subsidies, will likely continue in some countries, but should be scheduled to be phased out when the fuels they support approach commercial viability, as has occurred in Brazil and Germany.

It is also critical that small-scale biofuel development occurs alongside larger-scale production for export. Policies should be mindful of the benefits of both large and small-scale biofuel production and not "pick winners"—rather, they should support the most environmentally and socially beneficial production processes available, especially as increases in population and economic growth result in increasingly high energy demand. Technology transfer and investment from industrialized countries to facilitate market development will also be essential for biofuel development.

In general, development of the biofuel industry will require long-term and flexible commitments to these fuels. Successful use of biofuels to meet the growing liquid fuel demand will necessitate a comprehensive approach to market development. Demands from industrialized countries are likely to exceed economical biofuel production capacity and lead to trade, and policies will need to be developed to address fuel quality, social and environmental concerns, etc. (See Chapters 9 and 17.) Also, reducing petroleum subsidies, and subsidies to other fossil fuels, will increase the competitiveness of biofuels worldwide.

To secure policies and programs for sustainable biofuel development, there is a real need for leadership to facilitate international policy developments and integrate disparate efforts related to biofuels. Although many international actors are currently involved in different aspects of biofuels policy, there remains a need for coordination to maximize the benefits of these many initiatives.

Chapter 18. Standards and Certification Schemes

18.1 Introduction

As discussed throughout this report, the methods for producing different biofuels vary considerably, with some being more environmentally and socially sound than others. As international trade in biofuels increases, mechanisms are needed to assure both domestic consumers and importers that the fuels they use were produced using the most sustainable methods and equitable labor practices possible. One of the most pressing concerns is the potential impacts of feedstock production, including deforestation and competition with food uses.

While current biofuel trade is minimal, the call for such safeguards has already been raised, particularly in Europe. In 2005, consumers and activist groups in the Netherlands and the United Kingdom expressed rising concern about the environmental impacts of palm oil plantations on forests and wildlife in Southeast Asia—production driven in part by increased European demand for biodiesel.[1] UK imports of palm oil alone doubled between 1995 and 2004, to 914,000 tonnes, representing 23 percent of the EU total (most of this is for food uses, though plans for palm-based biodiesel are unfolding).[2] Such outcries have generated wider calls for the development of certification systems. Most initiatives call for voluntary systems but a few governments intend to initiative mandatory schemes.

Setting standards and establishing certification schemes are strategies that can help ensure that biofuels are produced in a responsible manner. They can also enable consumers to discriminate between fuels based on the sustainability of production. These schemes will be particularly important for countries that are actively striving to achieve reductions in greenhouse gas (GHG) emissions and that have included biofuels in their emissions reduction plans. Where they exist or could be created, strong national policies can act as an example and alternative to international certification schemes. Technical assistance from industrialized nations can also help countries developing biofuel markets to adopt sustainable practices.

This chapter discusses some of the main strategies being considered to guide biofuel production. It describes existing standards and certification schemes in the agricultural and forestry industries that could provide useful models for biofuels, as well as some of the initial efforts to design schemes specifically for these fuels. It concludes with a consideration of barriers and outstanding questions related to the creation of safeguards, and how assurance mechanisms might be pursued to facilitate biofuel trade that maximizes both environmental and rural development benefits.

18.2 The Need for Sustainability Standards and Certification

Today, a variety of sustainability standards and certification schemes exist or are under development in the areas of agriculture and forestry; however, no such system exists specifically for biofuels. Such initiatives are needed to help establish minimum social and ecological standards for these fuels and to guarantee responsible use of biomass from the raw material stage through its final application.

Such standards would aim to address some of the dominant environmental and social concerns related to biofuels and their feedstock, particularly when these are developed on a large scale. From an environmental perspective, the primary concerns include: ecological impacts of monoculture crop plantations; damage to water and soil from the application of pesticides and fertilizers; soil erosion; nutrient leaching; increased use of fresh water resources; and the loss of biodiversity and wildlife habitat, particularly if cropland area is expanded into previously undisturbed sites. (For a more detailed discussion of these concerns, see Chapters 12 and 13.)

Relevant social issues include potential impacts on agricultural and rural incomes; access to biofuel markets by small landholders and indigenous groups; job availability and quality (which could increase or decrease, depending on the level of mechanization, local conditions, etc.); potential use of child labor; and access to education and health care for workers. (For more information on these social issues, see Chapter 8.)

It is important to note that these problems are not necessarily bigger or worse with biomass production than with similar agricultural activities, such as large-scale food and feed production. Nevertheless, establishing a certification program could help minimize the potential negative impacts of biomass production while also working to promote sustainable biofuel trade.

18.3 Relevant Standards and Certification Schemes

Biofuels, especially those produced from current-generation feedstock, are produced primarily from traditional agricultural crops; however, unlike the majority of food crops traded they are not consumed and therefore have a different significance for consumers. People concerned about the impacts of conventional agriculture on human health and food quality might be less concerned about crops raised for energy. Nevertheless, large-scale agricultural production of biofuels can have equally important impacts on the environment in terms of water and air quality and especially biodiversity. (See Chapter 12 and 13.)

The rapid scaling-up of biofuel production in many countries is making certification an immediate imperative. "Piggy-backing" on existing schemes such as those advocated by the International Federation of Organic Agriculture Movements (IFOAM) could be an excellent first step toward establishing a verified, sustainable biofuels industry. Collaborative certification schemes could be a starting point, setting minimum standards for cultivation and harvesting practices for biofuel producers. As biofuel trade increases in volume and complexity, a more advanced and innovative certification scheme may build off of earlier efforts.

Among the existing schemes that could act as models for biofuel standards and certification are: the Rainforest Alliance's Standard for Sustainable Agriculture in Latin America, organic certification and labeling schemes in more than 100 countries, the Forest Stewardship Council's international forest certification system, a UK environmental assurance program linked to the country's renewable fuels obligation, and the newly established Roundtable on Sustainable Palm Oil. Each of these is described in detail in the following sections. (For an extensive list of other relevant standards and certification schemes, see Appendix A–8.)

18.3.1 Standard for Sustainable Agriculture

The Standard for Sustainable Agriculture (SSA) was developed in the 1990s by the New York-based Rainforest Alliance and collaborating organizations in Latin America. Through a coalition of independent conservation groups, known as the Sustainable Agriculture Network (SAN), these organizations promote the social and environmental sustainability of production in several key commodity areas, including coffee, bananas, cocoa, citrus, ferns, and cut flowers. [3] The network aims to improve the social and environmental conditions of tropical agriculture by:

- Certifying sustainable practices on farms and awarding a credible seal of approval (the "Rainforest Alliance Certified" eco-label) to farms that comply with the SSA;

- Changing the paradigm of farm owners, retailers, and consumers to encourage all stakeholders in the agricultural industry to take greater responsibility for their activities;

- Establishing contact between conservationists in the North and the South and offering them a way to work together;

- Increasing public awareness about the effects of consumer purchases on tropical peoples and ecosystems, and offering the choice of more responsible certified products; and

- Creating a forum for discussing the environmental and social impacts of agriculture.

In November 2005, after extensive public consultation, SAN approved the final version of the SSA, which includes principles in ten key areas: Social and Environmental Management System; Ecosystem Conservation; Wildlife Protection; Water Conservation; Fair Treatment and Good Working Conditions for Workers; Occupational Health and Safety; Community Relations; Integrated Crop Management; Soil Management and Conservation; and Integrated Waste Management. [4] These areas are very similar to those that would need to be covered in sustainability standards developed for biomass and biofuels.

18.3.2 Organic Certification and Labeling

Organic certification is the most well established system of certification, started over 30 years ago as a result of grassroots momentum by farmers interested in cultivating agricultural products in a more environmentally sustainable way. As the movement grew, certification evolved from self-evaluating farmer defined criteria to more sophisticated systems of third-party monitoring implemented by governments and non-governmental groups.

The proliferation of organic certification schemes led to a movement to establish consistent standards and to provide model laws and voluntary standards. The International Federation of Organic Agriculture Movements has advocated a decentralized system to support organic practices, and it now represents some 750 agricultural organizations in 108 countries. It has been instrumental in the adoption of formalized standards for organic agriculture such as the Codex Alimentarius as well as EU and FAO regulations.[5] Thus, "piggy-backing" on existing schemes like IFOAM could help to launch the international movement toward a more sustainable biofuel trade.

18.3.3 The Forest Stewardship Council's Forest Certification System

Another promising model for a variety of biofuel feedstock areas is the Forest Stewardship Council's system for forest certification. The Forest Stewardship Council (FSC), headquartered in Bonn, Germany, is an international network of non-profit organizations, businesses, and governments that works to promote responsible management of the world's forests by granting certification to forestry-related operations that meet strict FSC standards.[6] The FSC accredits third-party certifiers, who then conduct field audits of candidate forests.

FSC standards are established via consultation with all three chambers of its General Assembly (economic, environmental, and social) and an elected board, which oversees the system. The standards consist of ten principles, covering such areas as indigenous peoples' rights, environmental impact, and maintenance of high conservation value forests, and a set of criteria to measure implementation.[7] Specific indicators can be tailored to each country or region.

The FSC framework works to ensure that all policies and standards development processes are:

- ***Transparent,* meaning that t**he process for policy and standards development is clear and accessible;

- ***Independent*, meaning that s**tandards are developed in a way that balances the interests of all stakeholders, ensuring that no one interest dominates; and

- ***Participatory*, meaning that the** FSC strives to involve all interested parties in the development of FSC policies and standards.[8]

Under the FSC system, any timber company, furniture maker, paper manufacturer, printer, or retail outlet can undergo a voluntary third-party audit; if their operations pass muster, they will receive a certificate and license to label their products with the FSC logo. The Council's chain-of-custody control system guarantees the sustainable production of all FSC-labeled items along the path from forest to consumer, including forest management, timber operations, processing, transformation, manufacturing, and distribution.

Over the past decade, FSC has indirectly certified more than 50 million hectares of forest in over 60 countries, and several thousand unique products now carry the FSC logo.[9] Certification has caught on much faster in industrialized countries than in developing countries, however, due in large part to the expense. To address this problem, the FSC has established a mechanism that reduces the costs of certification by allowing small producers to be certified in groups. In addition, a special mechanism for small and low-intensity managed forests streamlines the assessment process and reduces some of the evaluation and monitoring costs. This has simplified the certification of non-timber forest products (such as fruits, nuts, and ferns), and could ease the way for certification of ecosystem services such as clean water and carbon sequestration.

18.3.4 Linking Assurance Schemes to a Renewable Fuels Standard

Another system that might provide a useful model for biofuels is now under consideration in the United Kingdom. The UK's Renewable Transport Fuel Obligation (RTFO) sets a target for 5 percent biofuel use in the UK by 2008, and policy makers have stressed the importance of sustainably produced fuels in meeting this target.[10] To this end, a feasibility study was conducted in 2005 assessing the merits and drawbacks of using the RTFO as an instrument to increase the use of renewable fuels in the transport sector.[11]

A key focus of the evaluation was if and how assurance schemes covering greenhouse gases, as well as broader environmental and social issues, should be linked to an RTFO. The study concluded that a "simple, transparent and verifiable GHG certification scheme" could be developed at a low cost to the government and fuel suppliers, and negligible cost to the consumer. It was estimated that such a scheme could be developed and piloted within 18 months, a time scale consistent with introduction of an RTFO.

18.3.5 The Roundtable on Sustainable Palm Oil

Another recent effort to establish sustainability standards, the Roundtable on Sustainable Palm Oil (RSPO), could prove particularly relevant to biofuel feedstock certification discussions. WWF, in partnership with several companies and other interested parties, established the RSPO in 2004 in response to rising concerns about the environmental and social impacts of palm oil plantations. The group now has at least 95 members, representing the palm oil industry and other organizations working in and around the supply chain for palm.

In late 2005, all RSPO members voluntarily adopted the newly created Principles and Criteria for Sustainable Palm Oil, which set sustainability standards for palm oil production. The RSPO is currently in the midst of a two-year pilot implementation process to field-test these principles and advance guidance on how the criteria should be interpreted and enforced.[12] Members are expected to support the Roundtable's standards and to actively promote the use of sustainably produced palm oil.[13]

The Principles cover eight categories of operation, including: commitment to transparency; compliance with applicable laws and regulations; commitment to long-term economic and financial viability; use of appropriate best practices by growers and millers; environmental responsibility and conservation of natural resources and biodiversity; responsible consideration of employees and of individuals and communities affected by growers and mills; responsible development of new plantings; and commitment to continuous improvements in key areas of activity. Specifics range from using integrated pest management practices, to developing and implementing plans to reduce pollution (including GHG emissions), to allowing workers to join trade unions.[14]

Efforts are also under way to create a Roundtable on Sustainable Soy, modeled on the RSPO. Like the RSPO, this multi-stakeholder group aims to provide stakeholders and interested parties with the opportunity to jointly develop solutions for sustainable soy production. The process was initiated by WWF and is now being managed by an organizing committee that includes several soy producers and retailers as well as non-governmental groups.[15]

18.4 Implications of the WTO Policy Framework for Biofuel Certification: International Trade and Equity

Although the issue of bioenergy trade is not explicitly one of the topics dealt with by the World Trade Organization, the intersection of energy and agriculture markets for trade make biofuel trade a very interesting and relevant issue. Biofuel trade is inextricably linked to food and forestry commodities and markets, sustainable development, and climate change discussions, all of which are potentially pivotal issues for WTO legislation.

18.4.1 Barriers to Trade

Because the majority of current-generation biofuel feedstock is agricultural commodities, the discussion of barriers to biofuel trade must begin with trade barriers in agriculture, a key area of WTO engagement. Harmonization of agricultural subsidies is being pursued; however, a number of approaches allow countries to subsidize the agricultural sector, such as: support for R&D; infrastructure (so called ‘general benefits’) that in general should not significantly and clearly affect export volumes; support for ‘production limiting programmes’ (e.g. set-aside regulations, ‘green box subsidies’), and support for replacing undesired crops such as narcotics.[16] Conservation efforts like the EU’s subsidies for transferring agricultural land to forest plantations are an example of allowed support which could affect developing biofuel markets.[17]

As a result of the latest round of trade negotiations, developing countries can maintain a support level of 10 percent of the total value of agricultural production, while for the EU, United States, and other industrialized nations, this is limited to 5 percent, which may be lowered in future negotiations.[18] Under current rules, direct export subsidies are not allowed; although subsidizing transport costs is permitted. In addition, countries have made specific commodity-tied commitments to reduce subsidies during agricultural negotiations; each of these separate agreements must be considered.

Further complicating biofuels trade will be its definition as a “product” by the WTO. Distinctions are made between ‘old’ products, for which agreements already exist, and ‘new’ products that have to comply with the most recent WTO rules. Additional complexities result because biofuels can fall under tariff schedules for agricultural commodities, industrial chemical, and energy carriers. This distinction could be of major relevance for bioenergy trade. If biomass-derived energy carriers are recognized as ‘new’ products, pathways around current protection measures from the EU for biomass-derived ethanol could be devised.[19]

The issue of trade barriers for biofuels was brought to light in the case of Brazilian ethanol exports to Europe, which has tariffs in place for commodities derived from sugar.[20] However, the issue was not pursued by Brazil. In the future, it is likely that Brazil or other WTO member countries will bring biofuels into negotiation rounds as part of a portfolio of topics under discussion.[21]

18.4.2 WTO Policies and Certification

Technical barriers to certification, such as specifying product and content definitions, are relevant for the wide variety of commodities and energy carriers that comprise an international bioenergy trade.[22] The WTO Technical Barriers to Trade (TBT) Agreement requires that domestic technical regulations use international standards as a basis where they exist, and where they are not ineffective or inappropriate.[23] The TBT Agreement also requires that such technical regulations not be an unnecessary obstacle to trade.

Regarding the general WTO rules on internal regulations (contained in the General Agreement on Trade and Tariffs, GATT), the regulation of process and production methods (PPMs) is politically controversial at the WTO. The setting of PPM-based regulatory requirements is not as such inconsistent with existing legal rules, as interpreted by the Appellate Body in Asbestos.[24] According to the Appellate Body, consumer tastes and habits must be considered in determining whether two products are ‘like’ and thus are entitled to ‘no less favorable treatment.’[25] If consumers differentiate products based on their production methods, or would do so if they had the information, then these products may well be “unlike” in accord with the Appellate Body's jurisprudence.[26]

Moreover, for a regulatory measure to violate National Treatment, it must not only treat ‘like’ products differently, but afford ‘less favorable treatment’ to the group of imported products when compared with the entire group of 'like' domestic products.[27] In the case of PPMs, the Appellate Body has emphasized that regulatory distinctions may be drawn even between products found to be 'like,' provided that the distinctions in question do not systemically disadvantage imports over domestic products. For an emerging biofuel market, it is therefore possible to design measures that specify process and production methods desirable to importing countries so long as they do not systematically disadvantage imports and favor domestically produced fuels. Also, these measures must conform to the most-favored nation (MFN) requirement in Article I of the GATT, and not discriminate on the basis of national origin between the like products of different exporting WTO members.[28]

18.4.3 Current Initiatives for Biofuel Certification

As the possibility of expanded biofuel trade becomes a greater reality, the push for certification in this area is gaining momentum. The Dutch government, for example, has passed legislation requiring that a certification system be developed to assure the sustainability of imported biomass fuels. Using existing quality-control models, such as the EuroGAP criteria for agricultural products or FSC wood certification, the Dutch company Essent has developed the the Green Gold Label. To qualify for the label, biomass has to be sustainable and traceable through the entire supply chain, from the plantations or forest to the consumer. Minimum conditions include that the biomass must be renewable (i.e., replanting must occur after harvesting); however, other environmental and social criteria are not currently included in the system. The monitoring process includes annual audits of biomass producers and suppliers, as well as quality control inspections.[29]

Following the Dutch example, the EU is currently considering environmental standards for imported biofuels, as well as working toward bilateral agreements in this area.[30] The EU is responding to both consumer and producer concerns: increasingly, biofuel producers in Europe are asking for safeguards that require exporting countries to meet minimum labor, environmental and other standards on par with their own. At the same time, the U.N. Food and Agriculture Organization (FAO) is working with the Global Environment Facility (GEF) to develop criteria for evaluating proposals for such schemes. FAO's suggestions to date have been based on a literature review rather than on field trials, but the organization aims to field-test them soon.

For their part, several biofuel exporting countries, as well as the FAO, have expressed concern about the trade implications of a rigorous biofuel certification scheme. A key worry is that certification schemes (or environmental standards more generally) will create trade barriers for developing country exports and will be used as a way for importing countries (usually industrialized countries) to protect domestic biofuel industries. This raises a variety of other equity-related issues, such as who will set the standards and who will accredit the certifiers.

Given these concerns, it is critical to establish standards that both exporting and importing countries agree on, and to ensure that these standards are applied consistently and transparently so they are not viewed as discriminatory. (In all likelihood, some developing countries would in fact perform better than many industrialized countries on a range of sustainability criteria, including the greenhouse gas balance and fossil energy input, because they tend to experience higher crop yields and use fewer chemical inputs.) It is also important to avoid creating a double standard between importing and exporting nations; the sustainability standards must apply equally for domestic production and use and for biofuels traded internationally.

18.5 Key Observations on Biofuel Standards and Certification

Based on the experience to date in implementing sustainability-related certification schemes, several key lessons can be learned, with specific relevance to the development of effective biofuel certification.[31] These include:

1. *Select the most appropriate standards or certification approach possible.* Safeguards and assurances can be applied through a variety of means, including laws or regulations, voluntary certification schemes, or criteria to qualify for subsidies or incentive programs. Relying on existing certification systems should be approached with caution, since they may represent (or be perceived to represent) only some of the stakeholder interests;

2. *Achieve consensus among diverse stakeholders about basic underlying principles.* Broad consultation and participation in the process is required for any voluntary system to be credible in the marketplace;

3. *Design and adopt specific, quantifiable criteria for sustainability indicators***.** Despite their specificity, these should be flexible enough to be adapted to the particular requirements of a region. Where strict, specific criteria and indicators are difficult to establish due to differing opinions of stakeholders, the use of so-called "process indicators" that show continuous improvement may help facilitate progress in moving forward.

4. *Ensure that compliance with the criteria is enforceable in practice, without generating high additional costs.* Issues of cost and who pays are critical to the success of a certification program, particularly when seeking participation of smaller-scale producers who may have fewer resources.

5. *Avoid leakage effects, through which benefits gained in one location "leak away" when damage occurs in another.* In the context of biomass trade, leakage could occur when crop production activities are expanded into previously undisturbed natural habitats, leading to increased greenhouse gas emissions from soil or other environmental impacts.

6. *Establish a system for monitoring and reporting.* In addition to assessing the sustainability of the biofuel feedstock supply and any possible leakage effects, it is critical to devise a system for measuring and reporting on energy efficiency and on the carbon and energy balances of the resulting fuels.

18.6 Outstanding Issues to Be Addressed

A variety of issues specific to biomass and biofuels still need to be addressed when considering standards and certification systems. At this time, there may be more difficult questions than definitive answers. Developing appropriate responses to these questions is a task left to key stakeholders in the international community.

Key questions include:

1. *Should biofuels be held to a higher standard than agricultural food products or petroleum-based fuels?* This is a particularly contentious issue in countries where the same crops are used for both food and fuel, or where two end products are processed in the same refineries (as in Brazil, where sugar cane refineries shift between sugar and ethanol depending on global markets). A potential double standard also exists with regard to petroleum fuels; rarely do consumers go to the fueling station to request sustainably produced petroleum gasoline or diesel. On the other hand, it is not uncommon for oil companies to experience boycotts and other public backlash in response to real or perceived human rights or environmental abuses. Moreover, one of the main drivers behind the push for increased production and use of biofuels is their potential environmental benefit—justifying the importance of ensuring that these fuels are truly sustainable.

2. *Will standards and certification schemes slow or speed market development of biofuels?* Because biofuel production is increasing at a rapid pace, taking steps towards certification that pick up on existing schemes is an important first move in establishing a sustainable biofuels industry. However, such schemes must not be an insurmountable hurdle for new market entrants. Establishing minimum standards between countries with established bilateral trade could be a starting point. As biofuel trade begins to include more actors, a more advanced and innovative certification scheme may expand on earlier efforts.

3. *What would these standards include? And how would less-quantifiable targets be measured?* Would standards focus primarily on greenhouse gas emissions, or would they also include pesticide use, impacts on biodiversity, water and air quality, and labor practices? How would the baseline be determined for GHG reductions, and would a minimum reduction target be established? Or, would preferential treatment be provided to specific feedstocks or production systems (i.e. integrated agro-energy systems)? And how would impacts on habitat and wildlife be measured in economic terms? How would a certification system ensure that biomass production does not crowd out the production of much-needed local food sources?

4. *Should standards and certification schemes be established at the national, regional, or international level—or all of these?* The EU is currently in the process of considering environmental standards for imported biofuels, and is also working toward bilateral agreements in this area. But is this the best option? How can we avoid a proliferation of standards that differ from one country or region to another? Similarly, how can turf battles among competing certification schemes and consumer confusion be avoided (a problem that has hampered efforts to develop meaningful certification in eco-tourism and organic foods)? It will be essential for standards to be either consistent or highly flexible. But would increased flexibility of standards minimize their potential to ensure sustainability?

5. *At what stage of production or distribution should certification occur?* Because biofuel generally comes from many diverse sources, it would be difficult to certify it only at the fuel pump. Should certification then be done at the farm gate, possibly even linking incentives for farmer certification to carbon credits? Or would it be best to certify biofuels at the distillery gate?

6. *Should standards and certification be voluntary or mandatory?* Would it be possible to first develop and adopt mandatory standards in a few existing markets, and then

publicize these more widely to encourage buy-in as other countries enter the global biofuels arena? The list of standards could be relatively simple, with specifics defined at the national level. Or perhaps a "club" of governments, companies, and other interested parties could voluntarily adopt standards and certification schemes, as the Roundtables on Sustainable Palm Oil and Soy have done. Such a reciprocal concept would likely not pose a problem with the WTO. Some experts believe that as part of a voluntary certification scheme, it would be possible to develop an eco-label for those biofuels that meet standards higher than those mandated by law; the fuels could be tracked and identified as a percentage of blends available at the pump. But others are skeptical of this approach.

7. *What is the best approach for developing standards and certification schemes?* Should actors work quickly to establish a few basic, minimum standards that can then be improved over time? Or is it more important to develop a thorough certification system, with broad stakeholder participation, even if this is a longer-term, more time-consuming process? Is it preferable to set up bilateral agreements first, while the most significant holes in the knowledge base are still being filled?

8. *Who will pay for the process of establishing such a scheme, or for certification itself, or enforcement?* Will such schemes increase the costs of biofuels at the pump, or put additional burdens on farmers and producers? One exploratory study has demonstrated that existing social and environmental standards for natural products do not necessarily result in high additional costs.[32] It is essential to ensure that standards and certification programs do not hurt small farmers and biofuel producers, or developing nations.

18.7 Conclusion

While there are many possible targets and outcomes associated with an increase in bioenergy trade, several are particularly critical. Trade in biomass and biofuels should, among other things: foster a stable and reliable demand for the services of rural communities, provide a source of additional income and employment for exporting countries, contribute to the sustainable management of natural resources, fulfil GHG emissions reduction targets in a cost-effective manner, and diversify the world's fuel mix. Achieving these diverse goals—particularly in a sustainable manner—may best be done through implementation of a sound standards and certification framework.

Many potential sticking points remain, however—not least the fact that environmental and social safeguards could be perceived as unfair trade barriers to biofuels exports. Yet at the same time, such standard setting could become a critical driver to facilitating development of sustainable trade in biofuels. Thus, a compromise must be reached between developing complicated certification schemes and ensuring both growing markets and long-term sustainable biomass trade.

Technical standards for sustainability could probably be produced in a reasonably short time, but these alone may not be enough. To guarantee consumer confidence in the sustainability of the biofuel products themselves—particularly as the industry grows larger—a certification scheme will likely be needed to back up the standards and oversee their application. The *incremental* development of such a certification scheme is probably the most feasible option, allowing for gradual learning and expansion over time. While not all biomass types may fulfil the entire set of sustainability criteria initially, the emphasis should be on the continuous improvement of sustainability benchmarks.

While a certification scheme should be thorough, comprehensive, and reliable, it should also not create a significant hurdle for nascent biofuel industries. Criteria and indicators must be adopted according to the requirements of each region, and be mindful of the implementation costs. For example, it will be important to pair any certification scheme with technical assistance, incentives, and financing, so that small- and medium-scale producers can qualify as readily as larger producers. Furthermore, it is important to ensure that any standards and certification schemes for biofuels address the issue of possible leakage effects, through which benefits gained in one location could “leak away” when damage occurs in another.

Moving forward, additional research will be needed to determine whether an independent international certification body for sustainable biomass is feasible. This should be done by a consortium of stakeholders in the biomass-for-energy production chain. At this stage, and at later steps in the development process, public information dissemination and support will be critical.

PART VII. RECOMMENDATIONS

Chapter 19. Recommendations for Decisionmakers

19.1 Introduction

Biofuels have the potential to help meet many of the challenges that the global community faces today—reducing the threat of climate change, reducing reliance on oil and improving international security, and alleviating poverty in some of the world's poorest nations. Alternatively, a massive scale-up in production and use of biofuels could increase the concentration of economic wealth while speeding deforestation and biodiversity loss and possibly accelerating climate change. The path taken will depend primarily on policies put in place by leaders at the national and international levels.

When thinking about biofuels it is important for policy makers to keep in mind that there are really two different biofuels "worlds": large-scale, high-tech production, and smaller-scale, low-tech biofuel production focused primarily on poverty alleviation through rural energy provision and local agro-industry development (involving local ownership, employment, etc.). There is certainly overlap, and the two worlds can and should exist in parallel. But the appropriate technologies and policy orientations required to promote them both are quite different, and thus policymakers need to clearly define their desired outcomes and design policies accordingly. In many cases, multiple goals can be achieved, but the more high-tech and large-scale biofuel industries become—and the more involved the huge energy, auto, chemical, finance, and other companies become—the greater the policy effort required to fulfill the social and environmental aims.

This report focuses almost exclusively on high-tech biofuels, since small-scale biofuel applications are often for non-transport purposes and, therefore, outside of the scope of this report. Further research is needed into the potential for, and deployment of, appropriate technologies for small-scale and non-transport biomass energy applications.

In order to achieve their goals, it is critical that decision-makers take a *comprehensive approach* that encompasses all relevant sectors and stakeholders. The fuels, their production methods, the means of distributing them, and the vehicle technologies appropriate for using them all need to be coordinated across industry segments and government agencies. This will be challenging, but it is absolutely necessary. The alternative will result in inefficient feedstock and fuel production, missed production targets, incompatibilities in the infrastructure, bottlenecks in the system, lost economic development opportunities, and environmental degradation.

Furthermore, biofuel strategies must be developed within the context of a broader transformation of the global transport sector, with the goal of making it dramatically more efficient and diversified. As has been the case with renewable energy for electricity generation, biofuels will be able to meet a greater portion of total transport energy needs if the sector becomes more efficient.

Some governments have already enacted policies to support biofuels production, use, and increasingly, trade. (See Chapters 9 and 17.) While specific policy decisions will have to be made on a country (or regional) basis, according to unique natural resource and economic contexts, this chapter elaborates overarching recommendations to policy makers and describes a number of policy options that governments should consider enacting in order to advance sustainable biofuel development. These recommendations are drawn from experiences to date with biofuels, with other fuels, and with other renewable energy technologies, and are also based on the challenges that biofuels face today.

19.2 Developing the Biofuel Market

The most efficient way to hasten a rapid expansion of biofuel production is for governments to create a policy environment that is conducive to private sector investment in the development of these fuels. Policy makers should focus on creating a predictable and growing market for biofuels. In turn, this market will draw in the substantial capital, entrepreneurial creativity, and competitive spirit required to advance technologies, build production infrastructure, and achieve the learning and the economies of scale that are necessary to drive down costs.

Policy actions that governments can take right away, at no- or low-net cost, to help develop the market include:

- **Enact Tax Incentives.** Tax incentives have been used effectively in Brazil, Germany, the United States and other countries to spur biofuel production and reduce biofuel prices at the pump. They can also be used to encourage certain types of biofuels development (i.e. small-scale, community oriented), and to speed the adoption of biofuel-compatible vehicles and other infrastructure. (Tax incentives for biofuels can be made revenue-neutral in a number of ways, for example, by increasing taxes on petroleum-based fuels. Governments that subsidize fossil fuels can save revenues and reduce the need to subsidize alternative fuels by reducing direct and indirect subsidies for the petroleum sector.)

- **Establish Mandates and Enforcement Mechanisms**. Blending mandates create consistent and expanding markets which, in turn, attract private sector investment in technology advancement, infrastructure development, etc. Voluntary targets have been somewhat effective, but have not achieved the level of success provided by mandatory schemes coupled with credible enforcement mechanisms. Enforcement is important to ensure that targets are met. Mandates can be designed to steadily increase requirements for the share that must come from next-generation fuels. Mandates should also be tied to environmental and social standards (see below).

- **Use Government Purchasing Power**. The enormous purchasing power of governments has been used successfully in a number of countries to expand the market for various products. Government purchasing of vehicles and fuels that are certified under sustainability schemes (which could eventually involve a GHG component), could provide a powerful market driver. Local governments can switch entire fleets to vehicles that run on biofuels, as many have already done. National governments could gradually increase the share of their fleets that are fueled by biofuels and ramp up to 100 percent; the one exception might be tactical military vehicles.

- **Collaborate to Set International Fuel Quality Standards.** While many nations have developed or adopted biofuel quality standards, others still need to take this step. In order to develop a significant international biofuel market, fuel quality standards need to be agreed upon and enforced on the international level. This is necessary for consumer confidence and will gain increased importance as international trade in biofuels expands. Automakers need assurances of consistent fuel characteristics so they can honor vehicle warranties.

- **Account for Externalities**. Although it is extremely difficult, decision makers should find ways to assign monetary values to currently uncounted externalities, including local and regional pollution, health problems, climate change, and other environmental costs, as well as potential benefits, such as job creation and rural revitalization. This can be done through tax increases or incentives. For example, in the case of climate change, this could be done through a carbon cap and trade system (note, however, that this would not likely benefit biofuels in the short term; see Chapter 11).

- **Facilitate Public-Private Partnerships.** Public-private partnerships have resulted in important technological breakthroughs that have led to dramatic cost reductions (for example, in the enzymes needed for the breakdown of cellulose via enzymatic hydrolysis), and will continue to play an important role in advancing next-generation technologies.

- **Increase Public Awareness.** Consumer demand could be a powerful driver of the renewable fuels market. Strategies to increase the public's awareness and comfort level with biofuels include various forms of public education, such as formal awareness campaigns, public announcements, university research, and signage along highways. Typically outside the government sphere, but also potentially effective, informal methods include discussions on radio, blogs, podcasts, and the use of biofuels in movies and television shows.

Mandates paired with subsidies have also proven to be an effective combination for biofuels industry promotion; however, subsidies should be phased-out once a domestic industry has been established. Subsidies are often difficult to discontinue once created, so phase-outs should be strategically designed into the enabling legislation. For instance, subsidies for current-generation biofuels can be phased out first, while those for next-generation feedstock and refineries continue.

Mandates and subsidies can be used together, or as in the case of Germany, mandates can follow subsidies. As of early 2006, the German government was in the process of replacing subsidies for first-generation biofuels with a fuel blending mandate, but intended to maintain the subsidy for next-generation biofuels to further their development. In the near term, the promotion of biomass generally for various bioenergy and materials uses will help develop the biomass feedstock production sector while the next-generation liquid fuel conversion technologies are developed.

Public concerns regarding possible environmental impacts of biofuel feedstock cultivation must also be addressed if biofuels are to gain broad public acceptance. (See section 21.8 for a discussion of certification and other proposed schemes to assure the sustainable production of biofuels.)

19.3 National and International Research, Development, and Demonstration

To date, the world's engineering and scientific skills have not been focused coherently on the challenges associated with large-scale biofuel development and use. Thus, there is enormous potential for dramatic breakthroughs in feedstock and technologies that could allow biofuels to play a major role in enhancing energy security, reducing greenhouse gas emissions, and providing much of the world community with economical transport.

There has been a tremendous surge in private-sector investment in biofuels in recent years, but this investment tends to be oriented towards short-term and high payoff research. There are many long-term research needs that governments are best-suited to address; governments and international organizations should help coordinate public and private efforts by bringing together the best minds and resources in national research facilities, universities, civil society, and industry. Because intermittent funding seriously hampers research efforts, funding for research, development, and demonstration must be consistent as well as long term. It is worth noting that much of this research will likely have applications across the broader agricultural sector.

Research is needed to develop feedstocks and sustainable management practices, as well as technologies for harvesting, processing, transporting, and storing feedstock and fuels. Research is also required to better understand the potential environmental and societal impacts of biofuels throughout the entire supply chain. Biofuels and bioenergy as a whole are a cross-sectoral topic, which can only be analyzed in an integrated way. Some of the key areas for further research are provided below.

19.3.1 Feedstock Production

- **Improve Conventional Feedstock**. Improve energy yields of conventional biofuel feedstock, while developing sustainable management systems that include minimizing the use of chemical inputs and water. This includes research into the potential for modifying food crops to maximize both food and cellulose (for energy) production.

- **Develop Next-Generation Feedstock**. Improve management techniques and develop high-yield perennial crops suited for biofuel applications that require low inputs, are location-appropriate, and can improve soil and habitat quality while sequestering carbon. (See Chapters 4 and 12.)

- **Advance Alternatives to Chemical Inputs**. Research the potential for integrated pest management and organic fertilizer development and use, including the use of mixed-crops, rotations, and other management techniques.

- **Assess the Risks of Genetic Modification**. Potential risks and costs of developing and using GM crops must be fully assessed to determine if benefits outweigh costs. It is also important to research and develop appropriate safeguards for the use of genetically modified industrial organisms required biological conversion of cellulosic biomass to ethanol.

- **Supplement Environmental Life-Cycle Studies**. Research is needed to fill in gaps in the existing body of analyses, with regard to global climate impacts and effects on local and regional air, soil, water quality, and habitat, including a better understanding of the impacts of land-use changes, and of the scale of N_2O emissions from feedstock production, and their potential impact on the global climate. (See Chapters 11, 12 and 13.)

- **Develop Methodology for Measuring Life-Cycle GHG Emissions**. There is need for consistent, internationally used, methodology and assumptions for measuring GHG emissions associated with the production and use of biofuels from various feedstocks, associated land-use changes, management strategies, and processing practices. (See Chapter 11.)

19.3.2 Feedstock Collection and Handling

- **Improve Equipment and Harvesting Practices.** Agricultural equipment and harvesting practices must be optimized for both crop and residue harvesting, to maximize economic benefits for farmers while minimizing soil compaction, and minimizing interruption of primary food crop harvests.

- **Ascertain Sustainable Residue Removal Rates.** Conduct research to determine sustainable extraction levels of agriculture and forestry residues to maintain soil quality under varying conditions.

- **Improve Waste Handling Practices**. Develop optimal means for safe handling and collection of various municipal waste resources (e.g. waste grease, cardboard).

- **Optimize Feedstock Storage and Transport Methods**. For example, improved methods are needed to prepare feedstock for transport by reducing bulkiness and water content.

19.3.3 Processing

- **Maximize Efficiency of Input Use**. Technologies and practices should be optimized to make the most efficient use possible of water, energy, chemicals, and other inputs, and to minimize waste through recycling of wastewater, waste heat, etc.

- **Advance Biorefinery Concept**. Continue support for the integration of a variety of related operations, including use of animal and crop residues as fuel feedstock and/or for process energy, and co-products (such as wet-distillers grain) as animal feed, bio-plastics, etc.

19.3.4 Fuel Distribution and End Use

- **Advance Fuel and Power Train Development**. Combine research and design needs to optimize engine designs/performance to take full advantage of the unique properties of biofuels (e.g., higher oxygen content, higher octane, etc.), and evaluate fuel specification criteria to identify potential fuel changes that could improve engine performance.

- **Optimize Vehicles**. This includes fine-tuning control systems and engine designs to run on varying blends for maximum fuel efficiency and minimum emissions across the full range of potential blend mixes.

- **Develop Materials**. Research materials for higher-quality tubes, hoses, and other connectors to reduce evaporative emissions.

- **Develop Fuel Additives**. Additives are needed to reduce emissions of NO_x and other harmful emissions from blends of fossil and biofuels.

19.3.5 Demonstration and Field Trials

In addition to resource assessments, policy analyses, and applied crop and processing research, it will be critical to advance experience on the ground, in varied settings. This will include field trials of new energy crops in different climate and soil conditions. Pilot conversion facilities, using cutting-edge technologies, should be funded and constructed in a wide range of settings in order to work out any related problems or challenges and to develop and make use of in situ ingenuity and local adaptation of technologies, crops and crop management, and handling systems. This should involve well-organized and well-monitored efforts in several countries (with varying climates, soil conditions, social structures, etc., including heavily degraded and desert lands), to build a body of practical experience over the next decade.

19.3.6 Outreach/Extension

On the national level, findings need to be disseminated to producers through demonstration projects, extension services (where they exist), and other farmer education mechanisms, including feedstock demonstration projects. In addition, farmers will need the appropriate know-how, capital, and incentives to risk planting new crops and to follow best practices; sustainable management and good crop choices should be tied to existing or newly created government incentives.

19.3.7 Information Clearinghouse

On the international level, a clearinghouse is needed (such as the Renewable Energy Global Policy Network, REN21, or a small international institution) to gather and make available to the global community, information regarding relevant findings and experiences with biofuel research and policies from around the world. This could be a subset of REN 21 or a separate body focusing on biofuels and agriculture.

19.4 Incentives for Rapid Deployment of Advanced, Low-Impact Biofuels and Technologies

Policies are needed to expedite the transition to the next generation of feedstock and technologies that will enable dramatically increased production at lower cost, combined with the real potential for significant reductions in environmental impacts. To date, high costs and risks associated with construction of new conversion facilities have hampered the development of next-generation fuels. Governments and international financial institutions can play a critical role in reducing financial risks and providing low-cost capital, helping industry to move quickly through early commercialization barriers.

Specific actions that governments can take to expedite the transition include:

- **Provide Incentives**. Create tax structures and other incentives that favor next-generation biofuels and integrated “biorefineries” and bioprocessing.

- **Enact Mandates**. Mandates could require that an increasing share of total fuel come from advanced feedstock and technologies.

- **Fund RD&D**. More sustainable feedstock and technologies are needed, including those that provide enhanced net reductions in GHG emissions and in fossil inputs.

- **Support Farmers**. Farmers will need information, crop and equipment assistance, market access, and other help to make the transition to producing new feedstock.

- **Facilitate Conversion of Existing Plants**. Retraining and retooling are important for converting existing plants to next-generation facilities.

- **Provide Capital**. Low-interest, long-term loans and risk guarantees are required to facilitate the development of commercial cellulosic refineries and "biorefineries."

- **Encourage the Development of New Uses and Demand for Co-products.**

- **Encourage Technology Transfer.** Transfer of technology and capacity building to countries with nascent industries (particularly those with great potential for producing sustainable feedstock and fuels) will be of utmost importance.

19.5 Infrastructure Development

Ethanol use can increase to 10 percent of non-diesel fuel, possibly more, with minimal changes to current car fleet or infrastructure; biodiesel blends can be higher. To go beyond this, however, governments need to address the 'chicken or the egg' dilemma: vehicles are needed that can run on high-blends of biofuels, but consumers will not buy them without a distribution system that assures access to these fuels; such a distribution system is not likely to develop without the vehicles to demand/use it. This dilemma can be resolved with technologies like flex-fuel vehicles (see below and Chapter 15).

To enable the expansion of biofuels, infrastructure changes will also be required on the production side (especially for next-generation biofuel production). New crops and production methods, as well as associated distribution requirements, will necessitate substantial infrastructure planning and development. The existing infrastructure available for the use of agricultural and forestry resources should be evaluated to determine what expansion and refinements are required for renewable biomass resources to play an expanding role in providing sustainable transportation fuel supplies.

To *encourage the necessary infrastructure transition*, governments could:

- **Advance Flexible-Fuel Vehicle Technology**. Governments could advance the development and availability of flex-fuel vehicles, including those appropriate for high-blends, through legislative mandates or softer incentives (like targets—for example, governments could call for 100 percent of new cars available in the domestic marketplace to be biofuel-compatible within 10 years). In promoting FFV's, governments should not allow trade-offs in fuel economy or air quality standards.

- **Promote Use of Flex-Fuel Vehicles**. In addition or instead, governments could establish incentives for consumers who buy such vehicles and use them with biofuels. Governments should also commit to transitioning to flex-fuel vehicles for non-diesel, non-strategic fleets.

- **Require Fuel Companies to Provide Biofuels**. Because of the control the fossil fuel companies hold over fuel distribution and sale in most countries, most governments may have to require that these companies distribute and sell biofuels. Governments could, for example, require that all fueling stations over a certain size convert at least one pump to biofuels (this would have to be phased in as fuel becomes available). This may not be appropriate in countries where blending mandates exist, and such a requirement could destroy market niches for smaller distributors.

- **Support Small Fueling Stations.** Smaller petroleum dealers and "refueling stations" should be supported, as they have a higher change for success (as has occurred in Sweden).

- **Support Development of New Fuel Standards.** As higher blends become more desirable, the fuel standards will need to be modified. Because this is a lengthy process, this should start as soon as possible.

19.6 Optimizing Ecological Impacts

While many perceive biofuels as environmentally beneficial because they are "renewable," these fuels have the potential to positively or negatively affect the natural world—everything from local soil and water quality, to biodiversity, to the global climate—and human health, depending on factors such as feedstock selection and management practices used. Whether the impacts are largely positive or negative will be determined, in great part, by policy.

As described in detail in Chapters 11 and 12, the most significant potential impacts associated with biofuel production result from changes in land use, including natural habitat conversion. With regard to climate change, land use changes (from razing of tropical forests to replacement of grasslands) for the production of biofuel feedstock can result in large releases of carbon from soil and existing biomass, negating any benefits of biofuels for decades. Therefore, governments must prioritize the protection of virgin ecosystems and should adopt policies that compel the biofuel industry to maintain or improve current management practices of land, water, and other resources.

Next-generation feedstocks and technologies offer the potential to improve soil and water quality, enhance local species diversity, and sequester carbon if lands are managed sustainably. This provides governments with yet another reason to speed the transition.

In addition, national and international standards and certification schemes will be necessary to safeguard the resource base (see Chapter 18 and below). Standards and best management practices take time to develop properly, so it is critical to initiate practical, step-by-step processes that entail consistent progress towards increased sustainability. Work on this has begun but should be supported with more substantial resources and greater international coordination.

Some specific actions that governments should take to help safeguard the environment and human health, while ramping up biofuels production, are provided below.

19.6.1 Feedstock Production

- **Conserve Natural Resources.** Local, national, and regional policies and regulations should be enacted to ensure that impacts on wildlife, and on water, air, and soil quality are minimized. For example, payment systems for irrigation and processing water could be adopted to encourage more-efficient use, and nutrient and water recycling should be encouraged.

- **Protect Virgin and Other High-Value Habitats**. Governments must find ways to protect natural forests, wetlands, and other ecosystems that provide air and water purification, soil stabilization, climate regulation, and other vital services. Options include: enforcing bans on wild land conversion for biofuel feedstock production including strong penalties for noncompliance; using satellite and global imaging technology to track land use changes; tying tax incentives, carbon credits, qualification for government purchase, sustainable production certification, etc. to the maintenance of natural ecosystems; and requiring land preserves. Large-scale feedstock producers can be required to set aside a share of their land as natural reserve, as the Brazilian state of São Paulo has done.

- **Encourage Sustainable Crops and Management Practices.** Extension services for farmers should provide them with the proper resources and incentives to select sustainable crops (particularly native species that reduce need for water, fertilizers, and pesticides), reduce the frequency of tilling and replanting, and provide habitat for wildlife. They should encourage sustainable management practices, including minimal use of inputs, buffer zones between waterways or wildlands and crops, intercropping, crop rotation, and adjusting harvest schedules to minimize conflicts with wildlife, etc. Subsidies can be linked to meeting specific criteria.

- **Improve Degraded Lands**. Encourage the rehabilitation of degraded lands through appropriate perennial feedstock production.

- **Maximize GHG Benefits.** Feedstock should be selected to maximize GHG reductions (see Chapters 4 and 11).

19.6.2 Processing, Distribution, and End Use

- **Develop Licensing Procedures**. Require that refineries meet strict environmental standards that include efficiency of water use and recycling, air and water pollution controls, etc.

- **Promote Use of Renewable Process Energy**. Provide incentives to use biomass as process energy and guarantee fair access to the grid for sale of excess electricity.

- **Establish** Emissions Standards for Biofuels. Just as regulations exist for conventional fuels, they are necessary for transport and combustion of biofuels. Regulations are needed to minimize spills and hydrocarbon emissions during transport and fueling, and to minimize evaporative and combustion emissions from storage, handling, and combustion stages of the supply chain.

- **Encourage Rapid Transition to High-Blend Fuels**. High blends with properly optimized vehicles can minimize a variety of harmful emissions. High biodiesel blends, particularly in urban areas of developing countries (where there may be weak emissions standards), can reduce public health risks, especially from particulate emissions. Cities can commit to shifting public buses and other government vehicles to 100 percent biodiesel over a few years.

- **Encourage Biofuels for a Range of Uses**. In developing countries where lead is still used as a transport fuel oxygenate (particularly in Africa), ethanol should be phased in rapidly to replace it. Biofuel (especially pure biodiesel) use for marine applications is particularly beneficial and should also be encouraged. Biofuel use for agricultural machinery (as in Germany), and construction and other heavy equipment (that is generally far more polluting and has much slower turnover rate) should be encouraged as well.

19.7 Maximizing Rural Development Benefits

If biofuels continue their rapid growth around the globe, the impact on the agricultural sector will be dramatic. Increased jobs and economic development for rural areas in both industrialized and developing countries is possible if governments put the appropriate policies in place and enforce them. The more involved farmers are in the production, processing, and use of biofuels, the more likely they are to benefit from them. Enabling farmer (and forest material producer) ownership over more of the value-added chain will improve rural livelihoods. This not only helps improve the well-being of farm families, it increases the positive effects as greater farm income is circulated in local economies and jobs are created in other sectors. As biofuel industries grow, this multiplier effect will have impacts on the regional, national, and international levels. Greater farmer ownership will also help prevent a repetition of the dynamics in the current global food industry, where very large processors are able to exert pressure on producers.

In regions where access to modern forms of energy is limited or absent, government and development agency support for small-scale biofuel production can help provide clean, accessible energy that is vital for rural development and poverty alleviation.

Specific options for decision makers include:

- **Cooperatives and Small-Scale Ventures.** Governments can provide support for cooperatives and small-scale biofuel production facilities—for example through tax structures that give preference to small-scale feedstock and fuel production, or preferential government purchasing from farmer/cooperative-owned facilities. Cooperatives allow small- and medium-size producers to share more in the economic gains of the biofuel industry and to negotiate on more equal footing.

- **Purchasing from Small Producers.** Governments can require fuel purchasers and distributors to buy a minimum share from farmer or cooperatively owned facilities.

- **International Development Funding.** National and international development institutions can provide financial and technical support for small-scale biofuel initiatives for rural energy provision and poverty alleviation.

- **Technical and Materials Assistance.** Governments, civil society, and others can provide assistance to small landholders in obtaining materials (energy crops seeds and seedlings), know-how, and market access.

- **Appropriate Fiscal Policies.** Governments can implement policies that allow for local approaches to be developed.

Government action to assure markets for biofuels and for energy crops (e.g. mandates, preferential purchasing, etc.) helps give producers the confidence to adopt new crops and crop management systems. In addition to providing markets for their products, ensuring fair prices for farmers is also essential to improving rural livelihoods.

19.8 Encourage Sustainable Trade in Biofuels

For the dozens of nations that are just beginning to develop biofuel industries, many decisions will have to be made, including the type, scale, and orientation (i.e. for domestic consumption, for export, or both) of production. Policies will need to be designed appropriately based on domestic economic and resource situations, and with the rapid pace of biofuels development, they will need to be put in place soon. Decision makers will also need to factor in the impacts that the policies of other nations (e.g. the EU biofuels initiative) and international trade policies (e.g. continuing trade liberalization negotiations) will have on their own biofuel and biofuel feedstock markets. In general biofuels trade restrictions should be removed over time, respecting the fact the countries with nascent industries will want to protect them.

Integrated planning is necessary at the national level so that short-term or sectoral interests do not take precedence over strategic national priorities. For instance, market incentives at the microeconomic level might encourage biofuel exports. But when other factors—such as national employment needs, domestic energy and security needs, trade balance, food security and land use concerns, the condition of domestic transport and export infrastructure, and GHG reduction obligations—are taken into consideration, exports might not make sense at that point in time. In many nations where displacing a modest amount of petroleum could make a significant difference, production for domestic use should take precedence over export. Alternatively the value of biofuels as an export commodity to earn foreign exchange may be preferable in other instances. National leaders will need to weigh these factors for their countries.

Well-established markets such as the United States and the EU have enormous fuel needs and growing energy security concerns. Due to policy initiatives actively promoting the use of biofuels, markets in these countries are large enough to accommodate both domestic production and imports (and the more rapidly biofuel-compatible transport infrastructure is phased in, the faster their biofuels markets will grow). International trade may help to ease fuel supply issues, linking a larger number of producers in order to minimize the risk of supply disruption. Also as renewable fuel use becomes more widespread, opportunities for countries with more developed biofuel industries to export their technologies will expand.

Some agriculture incentive programs in wealthy countries have been blamed for supporting food production in a way that harms competitors in developing countries. These could be transformed into programs that instead support biofuel production, a process that has begun in Europe and is being discussed in the United States. While this is a step in the right direction, replacing highly subsidized and protected commodity food production in rich countries with highly subsidized and protected biofuel production is not the aim. Biofuel support strategies must be planned with gradual phase-outs, or other means of moving beyond the subsidies once they are no longer necessary.

19.8.1 Trade and the Environment

Energy crops and biofuels may be categorized as agricultural goods under the WTO Agreement on Agriculture. Industry proponents may seek an exemption from the Agreement’s restrictions on domestic price supports by including biofuels subsidies in the so-called "Green Box." To qualify for Green Box status the incentives must be "non-trade distorting," meaning they do not affect global market prices. This will be a difficult test to meet if financial incentives for biofuels are tied to production levels, especially if the trade grows to a significant size. The more that incentives are clearly tied to producing public goods, such as clean water and air, wildlife habitat preservation, carbon sequestration and soil erosion control, unconnected to crop yields and refinery production levels, the more likely they are to pass muster.

Alternatively, if biofuels are categorized as industrial goods, they may qualify for treatment as "environmental goods." To be included in such a category they should be required to meet strict environmental standards for their production.

Developing countries have traditionally fought attempts to differentiate among traded goods based on Process and Production Methods (PPMs). However, some biofuels producers in developing countries could rank quite well in a scheme based on production standards. For example, the ethanol industry in Brazil has generally achieved very low net GHG emissions. (For more information on trade and biofuels, see Chapter 9.)

19.8.2 Standards and Certification

There are increasing calls in Europe and elsewhere for traded biofuels to be certified based in social and environmental standards. This could provide a means of ensuring that the production of these fuels provides net positive impacts for the planet and for society. However, if not developed in a participatory, transparent way, such a certification scheme could be viewed as a means for industrialized countries to erect new trade barriers to protect their domestic biofuel producers.

A certification framework based on sound standards could become a critical driver to facilitating development of sustainable trade in biofuels. A compromise must be reached between developing complicated certification schemes to ensure long-term sustainable biomass trade on the one hand and putting safeguards in place quickly to direct the rapidly growing market on the other. The *incremental* development of such a certification scheme is probably the most feasible option, allowing for gradual learning and expansion over time. Existing certification schemes provide useful models. While not all biomass types may fulfil the entire set of sustainability criteria initially, the emphasis should be on the continuous improvement of sustainability benchmarks.

While a certification scheme should be thorough, comprehensive, transparent, and reliable, it should also not create a significant hurdle for nascent biofuel industries. Criteria and indicators should be adaptable to the requirements of different regions, and be mindful of the implementation costs. It will be important to pair any certification scheme with technical assistance, incentives, and financing, so that small- and medium-scale producers can qualify as readily as large-scale producers. Furthermore, it is important to ensure that any standards and certification schemes for biofuels address the issue of possible leakage effects, through which benefits gained in one location could "leak away" to another. (For more information see Chapter 18.)

Moving forward, additional research will be needed to determine whether an independent international certification body for sustainable biomass is feasible. This should be done in collaboration with a consortium of all stakeholders in the biomass-for-energy production chain. At this stage, and at later steps in the development process, public information dissemination and support will be critical. It will be important to evaluate how likely broad participation by the petroleum industry, biofuel industry, importers, and consumers will be. Their participation is necessary in order for such a scheme to be accepted in the market. Costs and benefits for the various participants need to be analyzed.

19.9 Key Overarching Recommendations

- **Develop the Market**. Biofuel policies should focus on market development. An enabling environment for renewable fuels industry development must be created in order to draw in entrepreneurial creativity, private capital, and technical capacity.

- **Speed the Transition to Next-Generation Technologies.** Policies are needed to expedite the transition to the next generation of feedstock and technologies that will enable dramatically increased production at lower cost, combined with the real potential for significant reductions in environmental impacts.

- **Protect the Resource Base.** Maintenance of soil productivity, water quality, and the myriad other ecosystem services is essential. The establishment of national and international environmental sustainability principles and certification is important for protecting resources as well as maintaining public trust regarding the merits of biofuels.

- **Facilitate Sustainable International Biofuel Trade.** The geographical disparity in production potential and demand for biofuels will necessitate the reduction in barriers to biofuel trade. Freer movement of biofuels around the world should be coupled with social and environmental standards and a credible system to certify compliance.

- **Distribute Benefits Equitably.** This is necessary in order to gain the potential development benefits of biofuels. Enabling farmers to share ownership throughout the production chain is central to this objective.

To achieve a rapid scale-up in biofuels production that can be sustained over the long term, governments must enact a coordinated set of policies that are consistent, long-term, and informed by broad stakeholder participation.

Governments should promote biofuels within the context of a broader transformation of the transportation sector. Biofuels alone will not solve all of the world's transportation-related energy problems. Development of these fuels must occur within the context of a transition to a more-efficient, less-polluting and more-diversified global transport sector. They must be part of a portfolio of options that includes dramatic improvements in vehicle fuel economy, investments in public transportation, better urban planning, and smarter and more creative means of moving around a village or across the globe.

To achieve their full potential to provide security, environmental, and social benefits, biofuels need to represent an increasing share of total transport fuel relative to oil. In combination with improved vehicle efficiency, smart growth, and other new fuel sources such as biogas—and eventually even renewable hydrogen or electricity—biofuels can drive the world towards a far less vulnerable and less polluting transport system.

COUNTRY STUDIES

1. Biofuels for Transportation in China

The Chinese government began promoting biofuels several years ago in the face of rising energy demands and a sitting grain surplus. In the coming decades, energy consumption in China is expected to continue its dramatic climb. The aim of this study is to assess China's future role as a biofuel producer and importer, to identify potential impacts on global markets, and to point to related investment opportunities.

Current Situation

Ethanol

In 2004, China produced 1.3 million tonnes of ethanol for use as fuel. The government currently provides a subsidy of €137 ($166) per barrel of ethanol, and five provinces now mandate a blend of 10 percent ethanol (E10) in gasoline. The corresponding regulations are being handled at the province level, though the Chinese government intends to create a national statutory framework for a nationwide E10 blending obligation by 2020. This would translate into a demand of approximately 8.5 million tonnes of ethanol.

Production costs for ethanol currently range between €0.23 and €0.38 per liter ($0.28 and $0.46 per liter), depending on a raw material price between €0.16 and €0.32 per liter ($0.19 and $0.39 per liter). In the near future, Chinese ethanol production will be based mainly on sweet sorghum and cassava (manioc); in the past, production was based on surplus wheat, which is no longer available.

Biodiesel

China currently produces 50,000 tonnes of biodiesel per year, primarily from used cooking oil (edible oils). Production costs range from €0.17 to €0.35 per liter ($0.21 to $0.42 per liter) and are thus still relatively low compared with other regions (in Germany, for example, substantially higher costs of €0.68/l, or $0.82/l, are common). Existing biodiesel facilities and those currently under construction will provide a total annual capacity of approximately two million tonnes by 2010, corresponding to about 3 percent of China’s predicted diesel consumption.

Potential

China’s ethanol production target for 2020 is between 8 and 20 million tonnes, based on an expansion in the current area from 2.7 million hectares to 7.6 million hectares in 2020. According to the National Development and Reform Commission, domestic production will be sufficient in 2020 to supply a 10 percent blend (even with conservative assumptions). This assessment assumes that 25 percent of the required biomass will be covered by foodstuffs.

The Chinese Ministry of Science and Technology aims to produce 12 million tonnes of biodiesel by 2020. They estimate that, optimistically, the area planted in oilseed crops (40 million hectares in 2004) can be expanded to a maximum of 67 million hectares. Cultivating jatropha and a species of pistachio is currently under discussion. Based on a 10 percent blend, however, even a conservative estimate suggests that there will be a 7 million tonne biodiesel shortage in 2020.

According to forecasts, about 9 million jobs can be created in Chinese agriculture and industry through the production of biodiesel and ethanol.

Outlook

Decentralizing Chinese biofuel production will require improvements in the technologies for converting biomass and suitable wastes into liquid biofuels. Such decentralization would enable savings in energy expenditure and reduced transportation costs. China is very interested in the development of biomass-to-liquid (BTL) technologies, particularly in light of the large quantities of agricultural and forestry waste products generated in the nation's rural regions. Yet despite the fact that the first BTL conference was held in China in 2001, not a single BTL pilot plant is in operation today.

China's biodiesel market, meanwhile, would develop much more quickly if the government were to introduce standards for cultivation, processing technologies, and distribution networks. Rather than national biodiesel standards, China currently applies inadequately defined diesel standards. For ethanol, the Chinese regulations follow American standards, which differ from European standards. In practical terms this will be reflected in higher blending ratios, further increasing Chinese demand for ethanol.

Although the prospects for international ethanol trade are good, and production costs in China remain below the world market price, it cannot be assumed that China will become a global ethanol supplier. The reasons for this are limited production capacities and high domestic demand. In the future, China will likely continue to struggle to meet its rapidly rising demand for fuel with domestic biofuel production. It is therefore likely to emerge as a buyer, both regionally and globally. This will lead to corresponding price increases on biofuel markets. To facilitate greater international biofuel trade, China will require ports with suitable import and export capacities and associated investments.

Summary of Ethanol Situation in China

Summary of Biodiesel Situation in China

Parameter	Current	2020
Fuel ethanol output (t)	1 million	8–28 million
Total ethanol (t)	>3 million	
Fuel ethanol area (ha)	2.7 million	4.3 million (2010) 7.6 million, minimum (2020)
Subsidies for ethanol (per t)	€137 ($166)	0
Mandatory blending	10% in 5 provinces	10%
Production costs for ethanol (per liter)	€0.23–0.38 ($0.28–0.46)	
– feedstock price alone	€0.16–0.32 ($0.16–0.32)	
Ethanol net energy balance (in:out)	1:1.1 (corn) 1:2.1 (sugar cane) 1:0.7 (cassava)	

Parameter	Current	2020
Area planted in oilseed crops (ha)	40 million	up to 67 million
Cooking oil consumed (t/yr)	18 million*	70 million
Biodiesel production (t/yr)	50,000–60,000 (2004)	1.5–2.0 million (201 10.6–12 million (20
Biodiesel plant capacity (t/yr)	82,000 (2004) 241,500 (2006)	1.5–2.2 million (201
Biodiesel production costs (per liter)	€0.17–0.35 ($0.21–0.42) depending on feedstock	
Biodiesel energy (GJ/ha)	120	130

Note: According to the National Bureau of Statistics, China consumed a total of 18 million tonnes of edible oil in 2004. Of this, 4–5 million tonnes became waste oil, and from this 2 million tonnes was collectable.

The full study, "Biofuels for Transportation in China," is available at http://www.gtz.de/de/dokumente/en-biofuels-for-transportation-in-china-2005.pdf

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2. Biofuels for Transportation in India

Like China, India is a very populous nation experiencing rapid economic growth and rising energy demands. The Indian government actively promotes the production of biofuels. This study assesses the current situation and future opportunities for biofuel production and use in India.

Current Situation

Ethanol

India has been operating an ethanol program for several years; however, its activities have been severely hampered since 2002 by crop failures due to drought.

India's currently produces 665 million liters of fuel ethanol annually, derived primarily from molasses from sugar production. Subsidies for using sweet sorghum as a feedstock are also being considered. The nation's current sugar cane acreage is 4.4 million hectares, though the goal is to expand this slightly to 5 million hectares by 2007. Nine provinces currently have an official blending obligation of 5 percent ethanol in gasoline. Production costs are currently around €0.36 ($0.44) per liter, which is an average value from an international perspective.

Biodiesel

Biodiesel is a relatively new fuel in India and not yet commercially available, though it is already being produced in pilot projects (e.g. public/private partnerships involving DaimlerChrysler, Hohenheim University, and DEG; and Lurgi, SBT, and GTZ). Several states (Andhra Pradesh, Tamil Nadu, Chhattisgarh, Uttaranchal, and Rajasthan) have established a policy framework to support biodiesel.

Potential

Over the medium term, India's ethanol program aims to achieve a 5 percent blend in gasoline nationwide. Based on close links with the sugar industry, this is regarded as ambitious but achievable.

The targets for biodiesel production are less clearly defined, since production has only just begun. According to information contained in the *Wasteland Atlas*, 68 million hectares of so-called "wasteland" are available in India alone. The government is very hopeful that this degraded land can be cultivated with oilseed crops, particularly jatropha and pongamia. To achieve a 20 percent biodiesel blend (B20) by 2020, 38 million hectares of wasteland would have to be cultivated, and the current yield of 1–2 tonnes per hectare would have to increase to 5 tonnes per hectare. Availability of degraded land is limited to some extent due to unresolved ownership issues. In addition, the long-term economic viability of jatropha plantations on degraded soils has not yet been established.

Outlook

Due to high domestic fuel demand, India is likely to emerge as a biofuel importer rather than an exporter. This is based on attempts to diversify the sources for increasing fuel demand (in 2003, India imported 90.4 million tonnes of crude oil, and it is projected to import 166 million tons in 2019). Achieving the government's proposed blending targets will require significant investments in national production and processing facilities.

Summary of Ethanol Situation in India

The full study, "Biofuels for Transportation in India," is available at http://www.gtz.de/de/dokumente/en-biofuels-for-transportation-in-india-2005.pdf.

Parameter	**Current**	**2006–07**
Fuel ethanol production (l)	665 million	823 million
Total ethanol production (l)	2 billion	
Total sugar cane area (ha)	4.4 million	5 million
Mandatory blending	5% in 9 states	
Production costs for ethanol (per liter)	€0.36 ($0.44)	

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3. Biofuels for Transportation in Tanzania

Tanzania is an African country that has great agricultural potential, but that is affected strongly by changing sugar trade regulations. Currently, it does not have a policy framework for biofuels. This study assesses the resource base, policy environment, and other factors that will influence the potential for future biofuel production in the country.

Current Situation

Tanzania is completely dependent on petroleum imports (1.2 million tonnes in 2003), which account for roughly 40 percent of all imports and are responsible for a significant share of the country's foreign exchange spending. The transport sector consumes more than 40 percent of imported refined petroleum products. In 2002, Tanzania consumed roughly 134,000 tonnes of gasoline and 390,000 tonnes of diesel, and the Tanzania Petroleum Development Corporation forecasts annual growth of 5 percent in both gasoline and diesel demand to 2010.

In summer 2005, fuel prices for unleaded gasoline ranged between 1,120 and 1,195 Tanzanian shillings per liter (€0.77–0.83, or $0.93–1.00, per liter), and diesel prices ranged between TZS 1,075 and 1,095 per liter (€0.75–0.76, or $0.91–0.92, per liter). Tanzania has a complex taxation system for petroleum products consisting of three main taxes (excise duty, road toll, and Value Added Tax), which together comprise about 40 percent of the final fuel price charged to consumers.

Currently, there is no commercial biofuel production in Tanzania. However, several stakeholders are engaged in the development of biofuels. The main players with regard to commercial biodiesel production include FELISA (palm oil), KAKUTE, Diligent, PROKON, and D1 Oils (jatropha oil). For sugar cane-based ethanol production, the key players are the country's four main sugar companies: Kilombero Sugar Company, Mtibwa Sugar Estates, Kagera Sugar Limited, and Tanganyika Planting Company.

Current biofuel activities and opportunities in Tanzania can be roughly divided into large- and small-scale approaches. Large-scale biofuel production, such as ethanol production from sugar cane promoted by the sugar industry, will focus primarily on biofuels for transportation. Supportive policies and regulations will be required to secure the rather large investment required for start-up. Smaller-scale biofuel activities conducted by organizations such as FELISA and KAKUTE, in contrast, are concerned mainly with generating rural income and revenue opportunities from oilseed crops, through production of either plant oils (for food and/or fuel) or commodities such as soap from jatropha oil.

Potential

A recent assessment by the United Nations Food and Agriculture Organization found that 44.4 million hectares of land in Tanzania is potentially available for crop production (both food and non-food). While these figures present only a broad picture of land use in a very large and diverse country, they suggest that land availability is not likely to be a barrier to bio-energy production in Tanzania.

The following estimate of the potential for bio-energy production from the "potentially available land" (44.4 million ha) can be used to gauge the limits of any real production:

Parameter	Potential (estimated)

Land area (ha)	44.4 million (30 million very suitable)
Sugar crops	570,000
Cereal crops	24 million
Root crops	14 million
Energy	3.3 exajoules
Palm oil	186 gigajoules/ha
Jatropha oil	59 GJ/ha
Ethanol from sugar cane	173 GJ/ha
Ethanol from C-molasses	20 GJ/ha

Using a range of annual biomass production of 75–300 gigajoules (GJ) per hectare, the limits of bio-energy production in Tanzania would be in the range of 3.3–13.3 exajoules (EJ) per year. This compares with total annual primary energy consumption in the country of 0.602 EJ.

For the introduction of a biofuel industry in Tanzania, the following expected energy yields for the production of different transport fuels in Tanzania are important, namely biodiesel from palm oil (186 GJ/ha), ethanol from cane juice (173 GJ/ha), biodiesel from jatropha oil (59 GJ/ha), and ethanol from C-molasses (20 GJ/ha).

Sugar crops provide the simplest and most cost-effective feedstock options for ethanol production. The area under sugar cane has grown from 23,000 hectares to 39,000 hectares in the last five years, suggesting increasing availability of suitable feedstock for ethanol production. Current production of C-molasses by Tanzania's cane sugar industry (about 90,000 tonnes in 2004–05) could be converted into more than 20 million liters of ethanol per year, enough for a 10 percent blend of ethanol into gasoline (E10)—or nearly 7 percent of national gasoline consumption on an energy equivalent basis.

In August 2005, the retail price of gasoline in Dar es Salaam was TZS 1,120 per liter. At that price, ethanol would be competitive at a retail price of TZS 729 per liter, or about €0.53 ($0.64) per liter. At current petroleum prices, therefore, production of ethanol in Tanzania is likely to be competitive with gasoline.

Current production of oilseed crops is much lower than existing demand, and a biodiesel program of any real impact would require planting considerably more land with oil crops than is now the case. Oil palm and jatropha are the two oilseed crops most likely to be used as feedstock for biodiesel in Tanzania. Of the oilseed crops available, oil palm has the highest potential yield of oil per hectare of land harvested. However, there is currently great demand for palm oil for food and other uses, and local production meets less than 5 percent of this.

There is a current proposal for a palm oil biodiesel project in the Kigoma region. The project would involve cultivation of 8,000 hectares of oil palm, first to produce palm oil to meet local food and soap production demands, then eventually to produce biodiesel. If the project achieves the target oil yield of 5,000 liters per hectare, palm oil production could approach 40 million liters per year. This production would in itself not be enough to displace current imports (in 2002, Tanzania imported roughly 172 million liters of palm oil). Alternatively, 40 million liters of palm oil could be converted into about 39 million liters of biodiesel. Diesel fuel consumption in Tanzania is projected to be about 700 million liters in 2010. Thus, if all the projected palm oil production in the Kigoma project were to be converted to biodiesel, a national blend of 5.7 percent would be possible (5.2 percent on an energy equivalent basis).

The other favored crop for biodiesel production is jatropha. Tanzania has had some experience cultivating jatropha for small-scale oil production, which has been particularly promising in demonstrating the potential for rural poverty alleviation and empowering women. Cultivation of jatropha around the world has tended to be small-scale, so production and yield data for plantation-scale cultivation is limited. The oil yield from jatropha plantations is reported to be about 1,600 kilograms per hectare from the fifth year onwards, though some local experience in Tanzania suggests that actual domestic yields may be significantly less than this. On the basis of a yield of 1,600 kilograms of oil per hectare, 19,700 hectares of jatropha would need to be harvested to produce enough biodiesel for a 5 percent national blend with petroleum diesel in 2010.

Outlook

Exploiting the large resource potential for biofuel production in Tanzania is hampered mainly by lack of information. The absence of set policies and regulations makes investment in the biofuel sector difficult, as the prospective return on investment remains largely unclear. In the meantime, the Tanzanian government is well aware of the benefits offered by the introduction of biofuels for transport applications, and is seriously assessing the various options for developing policies and strategies for increased use of biofuels.

Activities towards implementation of biofuel policies in Tanzania are driven mainly by the Ministry of Energy and Minerals. At an expert workshop and policy discussion in Dar es Salaam, organized in the framework of this regional study, MoE representatives strongly supported the proposed establishment of a high-level Biofuels Task Force that would provide advice and recommendations for the elaboration of biofuel policies and regulations suitable for the Tanzanian context.

The production and use of biofuels in Tanzania has the potential to offer large opportunities for investors. For the time being, these opportunities must be carefully identified on a case-by-case basis (in close cooperation with local partners) until the Tanzanian government has committed itself to actively promoting development of the national biofuel sector and biofuel market.

The full study, “Biofuels for Transportation in Tanzania,” is available at: http://www.gtz.de/de/dokumente/en-biofuels-for-transportation-in-tanzania-2005.pdf.

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4. Biofuels for Transportation in Brazil

Brazil is currently the world's largest producer and exporter of biofuels worldwide. It has a long history of biofuel production and a well-established national ethanol program.

Current Situation

Ethanol

Over the last 30 years, Brazil has implemented a very successful renewable energy program called Proalcóol, which was also the world's first large-scale biofuel program. As a response to the international oil crisis, the program was launched in 1975 to reduce the country's imports of oil and to promote the production of ethanol using sugar cane as feedstock. In a transition period from the mid-1990s to 2002, government price controls and subsidies for production and logistics were eliminated for sugar and ethanol. In 2003, the first "flexible-fuel" vehicles (able to run on any blend of ethanol and gasoline) were introduced to the Brazilian market. Their numbers have increased rapidly: in 2005, sales of flex-fuel cars totalled 855,000.

Proalcóol has had a variety of positive effects, including the creation of roughly 625,000 direct jobs in harvesting and processing, the development of a national technology, and the emergence of a completely mature industry. In addition to contributing to better climate protection (i.e. the reduction of an estimated 46.6 million tonnes of carbon dioxide emissions per year), replacing gasoline with ethanol has led to important foreign earnings savings for Brazil. Between 1976 and 2004, avoided fuel imports represented a savings of €50.2 billion ($60.7 billion in December 2004 dollars).

Today, ethanol from sugar cane grown in the center-south region of Brazil is by far the cheapest biofuel, making the ethanol industry competitive. Production costs are estimated to be around €0.15 ($0.18) per liter, considerably lower than in other countries. Sugar cane is currently cultivated on about 5.5 million hectares, with 52 percent of the area cultivated for ethanol production and 48 percent for sugar production in 2004. Currently, 48 percent of the Brazil's total gasoline needs are met by ethanol. Biofuels for transportation represent 22 percent of the country's total fuel consumption (including gasoline, diesel, biodiesel, and ethanol).

Biodiesel

Through its Biodiesel Production & Use Programme, the Brazilian government is following a similar strategy to mitigate dependence on fossil fuels and push socio-economic development in rural areas through a graduated tax exemption based on the region and scale of production. Creation of a national biodiesel market is just beginning, however. The chain of production is being structured to foster sustainable development by enabling participation by smallholders in oil production. Currently, the acreage for oilseed plants (primarily for food and feed)—mainly soybean—totals some 23 million hectares.

With regard to international trade, opportunities exist for exporting ethanol to countries that use biofuel either directly (in blends of more than 70 percent), or in blends of up to 10 percent.

Potential

Projections for Brazil's sugar/ethanol sector suggest that rising internal and export market demands for sugar and ethanol can easily be met. It is assumed that the industry should be able to produce 33.7 million tonnes of sugar (12.8 tonnes for internal consumption and 20.9 tonnes for export) and 26.4 million cubic meters of ethanol (4.4 million for export) by 2015. This would require an increase in sugar cane production of about 230 million tonnes in 10 years—a doubling in ethanol production and a 44 percent increase in sugar production.

Considering the potential for biodiesel in Brazil, soybean oil can play an important role in the first years of implementation of the national biodiesel program, as the country is already one of the world's major producers of soybean oil. However, the low oil content, comparatively poor energy balance, and low employment-generation impacts of soybeans must be taken into account. Furthermore, soybean production could expand into sensitive ecosystems if not directed otherwise. Similar problems may occur with other crops relevant for biodiesel production, such as castor oil and palm oil.

Outlook

Ethanol trade is likely to continue to expand internationally. Worldwide, sugar production increased by 50 percent between 2004/5 and 2005/6 alone, with biofuels as a major driver. Ethanol trade has increased even more steeply. In the future, Brazil is likely to provide more than 50 percent of international ethanol trade.

Brazil is a potential exporter of biodiesel as well. Given the limited potential for increased biodiesel production in Europe, Brazil faces an unprecedented opportunity to build market share on the European continent. Because of restrictive specifications and national policies for biofuels around the world, however, the market for biodiesel exports remains rather dispersed, varied, and impaired by various trade barriers.

Brazil's biodiesel program set a 2 percent blending target in January 2006, and there is a potential market of about 800 million liters of biodiesel (B2) per year. From 2013 on, a mandatory increase to a 5 percent blend (B5) will be considered, which would create a firm market of 2.4 billion liters per year. Substituting 2 percent of petroleum diesel with biodiesel would lead to gains in Brazil's foreign currency reserves from reduced fossil fuel imports of about €132 million ($160 million) annually.

Furthermore, the substitution of 1 percent of Brazil's diesel consumption through the harvesting of various oil crops could result in the creation of approximately 190,000 jobs in rural areas. Achieving this goal, however, requires an emphasis on the importance of combining the biodiesel production program with national land use reform.

With regard to the ethanol sector alone, some €8.3 billion ($10 billion) in private investment will be needed by 2015 to meet the national and export market demands for sugar and ethanol mentioned above. And foreign investments will certainly be necessary to expand Brazil's biofuel sector overall. Germany, for example, has a long tradition of investment in Brazil and could provide processing technology and equipment, as well as know-how on planning and capacity building, in addition to direct investments. Additionally, a major factor in the development of the Brazilian biodiesel program will be the definition of biodiesel standards (technical, environmental, and social) and the formulation of a sustainable global trade strategy.

Summary of Biofuel Situation in Brazil

Parameter	2004	Future
Fuel ethanol production (l)	14.91 billion	20.5 billion of alcohol plus export of 5.5 billion
Fuel ethanol area (ha)	5.5 million of sugar overall: 52% for ethanol 48% for sugar	—
Production costs for ethanol (per liter)	€0.15 ($0.18	€0.088

		($0.107)
Ethanol net energy balance (in:out)	1:8.3	1:10.2
Acreage for oil seed plants (ha)	Soy: 22 million Palm: Nearly 60,000 Castor: 134,000 Sunflower: 52,800	Soy: 100 million Palm: 66 million Castor: 4 million
Biodiesel production (t/yr)	Still in experimental phase	Government target: 2 million (2013+)

The full study, "Biofuels for Transportation in Brazil," is available at: http://www.gtz.de/de/dokumente/en-biofuels-for-transportation-in-brazil-2005.pdf.

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5. Biofuels for Transportation in Germany

Germany is currently a major player in the European Union's biofuel strategy. The country's domestic policy framework provides strong support for increasing the share of biofuels in road transport. While the national focus has historically been on biodiesel, other biofuels such as ethanol, Fischer-Tropsch diesel, and biogas are gaining in importance. This summary discusses the current extent of German biofuel production and explores the potential for continued domestic production in the future, including implications for the agricultural sector and related industries.

Current Situation

Today, there is broad consensus in Germany that biofuels are a key element for a sustainable future, as illustrated in key government documents. As of 2006, the main commercially available biofuels in Germany were biodiesel made from rapeseed methyl ester (RME); ethanol (both pure and as ethyl tertiary butyl ether, or ETBE), and straight vegetable oil (SVO). (In addition, a few liters of experimental "Sundiesel" were produced by the manufacturer Choren to demonstrate the potential of Fischer-Tropsch diesel from biomass, and the first German fueling station for biogas was scheduled to open in mid-2006.)

Biodiesel

Overall market development of biodiesel in Germany has been impressive. Between 1991 and 2004, sales of RME increased 50-fold, and in 2006 a market volume of nearly 2 million tonnes was expected—representing a 100-fold increase over 1991. Of the 1.1 million tonnes produced in 2004, the majority was used directly for blending with fossil diesel, while some 0.4 million tonnes was sold at filling stations. About 60 percent of the biodiesel sold at filling stations is purchased by truck and bus fleet operators.

Ethanol

Compared to biodiesel, ethanol contributes only minimally to the current biofuel market in Germany. The main feedstock for ethanol production is cereals. Since early 2005, ethanol from cereals has increased. As with biodiesel, a blend of 5 percent ethanol to gasoline is currently allowed in Germany (so-called E5).

In terms of market share, overall domestic ethanol production has actually *decreased* in Germany over the past few years. In 2004, a total of 2.2 million hectoliters was produced, some 12 percent less than in 2003. (Note that data on ethanol use for fuels and other applications are not currently separated.) Thus, Germany accounted for only 10 percent of European ethanol production in 2004.

In recent years, biofuels were exempted from the German fuel tax so that they could compete with taxed diesel fuel. With the rapid increase in biodiesel production, tax losses totaled € 559 million in 2005, and will rise further if the tax exemption is maintained as planned until 2009. In late 2005, the new German government called for a change so that only existing "pure" biofuel capacities and next-generation biofuels (as well as biogas) will continue to benefit; in early 2006, it announced the introduction of a mandatory 2 percent biofuel blend in gasoline and a 4.4 percent blend in diesel, starting in 2007.

Potential

In addition to having adequate technologies for converting organic residues and wastes to biofuels, the key factor determining the potential to grow energy crops is having the available land, without competing with food, feed, and fiber demands. Energy crop potentials for Germany have been derived via a complex modeling of future developments in food, farming practices, and competing land uses from nature conservation, human settlements, infrastructure, etc.

Even assuming an increase in organic farming of up to 30 percent of all food by 2030 (from roughly 4 percent currently), Germany's net land balance is quite positive. Analysis indicates that nearly 4 million hectares of land could be used for energy crops, out of some 17 million hectares of total agricultural area in the country.

In addition to having available land, Germany's future bioenergy potential depends on the types of energy crops grown on this land. Germany is a pioneer in analyzing the most suitable crops from both an environmental and nature protection perspective. Analysis shows clearly that crops like sugar beets do not perform well and that perennial grasses and short-rotation woody crops (SRWC) are very favorable, as are double-cropping systems.

Outlook

Today, some 2,000 of Germany's 15,000 fuel filling stations supply RME100. It is expected, however, that use of RME100 in private cars will decrease, as the automotive industry will not authorize the use of pure RME in future EURO IV/V engines. (EURO IV is the EU's existing air emission standard for automotive vehicles; EURO V is the future requirement for diesel cars and trucks and is currently under negotiation.) Thus, the future market for RME100 will concentrate on company fleets in the transport sector.

As the blending of RME with fossil diesel increases from the current 2 percent, competition between the distribution of pure RME100 at filling stations and the blend market (via refineries) is already occurring.

In the future, wheat, rye, barley, and some sugar beets are expected to be the major sources for ethanol fuel in Germany. Firms are building new large-scale ethanol plants dedicated to fuel use, with production capacities of 590,000 cubic meters. This would increase Germany's overall ethanol production capacity to more than 900,000 cubic meters by the end of 2006.

Over the longer term, flexible-fuel vehicles (FFVs) can contribute substantially to achieving a broader market share for ethanol. In 2005, the Ford Motor Company announced that it would offer FFVs to the German market. Volvo and Saab have also announced that they will provide these vehicles, and Volkswagen, DaimlerChrysler, and others are expected to follow suit.

In 2006, the capacity of German oil mills and transesterification plants was expected to reach some two million tonnes per year. Given the import potential from Eastern Europe and Asia and existing rotational restrictions in agriculture, domestic biodiesel production might well level off at this amount, which fits neatly with the 2010 European Union target of 5.75 percent when applied to total diesel consumption in Germany.

Still, it will not be possible for Germany to meet the *gasoline* share of the EU biofuel target with domestic biodiesel. Accordingly, the near future will likely see an increase in ethanol from biomass, especially from wheat and sugar beets, even if next-generation conversion technologies are not yet commercially available. (Large-scale first-generation ethanol plants using wheat as a feedstock could deliver nearly competitive biofuels if feedstock costs were below € 8 per gigajoule, i.e. below €75 per tonne of wheat. Further, European sugar market subsidies will be gradually reduced, leading sugar beet farmers to seek alternative uses for their product.

Biogas, too, is increasingly being acknowledged as a potential biofuel, able to be processed to a high-methane fuel and fed into the natural gas pipeline system. Studies indicate that there is not only significant potential for biogas in Germany, but that the life-cycle emissions and costs could be lower than those for ethanol and biodiesel.

Although biodiesel has historically been the main driver for biofuels in Germany, moving beyond a 5 percent share in all transport fuels will require the adoption of other biofuels, either from other domestic sources or from imports.

In the *short term* (to 2010)**,** biodiesel and ethanol are expected to be the key biofuels in Germany, mainly as blends with fossil diesel and gasoline. Yet their essentially large potential is restricted by limited land for energy crop cultivation (e.g. rapeseed and wheat) as well as by competing biomass use in the stationary (power and heat) sector, which currently offers higher greenhouse gas reductions and lower costs. Thus, the German Fuel Strategy envisages a total biofuel market share of 5.75 percent—in line with the EU target—but not much more than this.

In the *medium to long term*, special emphasis is being given to options with the greatest impact on fossil fuel substitution, namely increased engine efficiency, production of synthetic fuels from biomass (BTL), hybrid powertrains, and hydrogen in fuel-cell vehicles. BTL is the prioritized medium-term option, while hydrogen is seen as the key long-term fuel. As the development of both remains immature, Germany's strategy calls for continuing R&D with a focus on gradually scaling up pilot plants, and for maintaining tax exemptions to bridge the cost gap during early stages of commercialization. Biofuel potentials are estimated to be large enough to meet the indicative EU-2020 target of 8 percent biofuels.

Note: This summary was derived from material prepared for the original *Biofuels for Transportation* draft report, dated June 2006.

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APPENDICES

A–1. Per Capita Consumption of Gasoline and Diesel, 2002

Country	Population (2002)	Gasoline Use	Diesel Use
		(thousand liters per person per day)	
China	1,284,275,902	0.11	0.19
India	1,034,172,547	0.03	0.12
United States	287,675,526	4.89	2.09
Indonesia	231,326,092	0.18	0.31
Brazil	179,914,212	0.25	0.59
Pakistan	153,403,524	0.03	0.15
Russia	145,266,326	0.66	0.54
Japan	127,065,841	1.29	1.52
Mexico	102,479,927	0.85	0.44
Philippines	82,995,088	0.12	0.23
Germany	82,350,671	1.22	2.28
Thailand	62,806,748	0.32	0.70
France	59,925,035	0.79	2.55
United Kingdom	59,912,431	1.30	1.35
Italy	57,926,999	1.06	1.65
Ukraine	48,058,877	0.36	0.33
Korea, South	47,969,150	0.58	1.33
South Africa	44,433,622	0.62	0.45
Spain	40,152,517	0.75	2.32
Poland	38,625,976	0.40	0.62
Argentina	38,331,121	0.26	0.73
Canada	31,902,268	3.39	2.41
Kenya	31,386,842	0.05	0.07
Saudi Arabia	24,501,530	1.66	2.61
Australia	19,546,792	2.64	1.98
Ecuador	12,921,234	0.50	0.56
Zimbabwe	11,926,563	0.09	0.15
Cuba	11,226,999	0.11	0.38
Guatemala	11,178,650	0.27	0.29
Czech Republic	10,256,295	0.69	0.93
Sweden	8,954,175	1.68	1.70
Slovakia	5,410,052	0.50	0.63
Denmark	5,374,693	1.34	2.54
Nicaragua	5,146,848	0.13	0.22
Lithuania	3,633,232	0.74	1.60
Mauritius	1,200,206	0.25	0.94
Swaziland	1,130,269	0.23	0.20
Total	4,404,764,780	0.61	0.58
World	**6,214,891,000**	**0.52**	**0.53**

Source: U.S. Census Bureau, International Programs Center, www.census.gov/ipc/www/idbprint.html; U.S. Department of Energy, Energy Information Administration, “International Petroleum Data,” www.eia.doe.gov/emeu/international/contents.html

A–2. World Producers of Petroleum and Biofuels
(Thousand Barrels per Day)

	Year 2004		Year 2002					
	PRODUCTION		CONSUMPTION		PRODUCTION	IMPORTS		
	Biofuels		Motor	Diesel	Crude Oil	Crude Oil	Motor	Diesel
Country/Region:	Ethanol*	Biodiesel	Gasoline	Fuel Oil		Imports	Gasoline	Fuel Oil
Canada	4.0		680.2	484.4	2,950	-227	32.5	7.1
Mexico	0.6		550.6	282.0	3,593	-1,808	157.1	37.2
United States	230.6	1.6	8,847.8	3,775.9	9,000	9,131	498.3	267.4
North America	**235.2**	**1.6**	**10,079.6**	**4,547.8**	**15,543**	**7,096**	**688.9**	**317.3**
Argentina	2.7		62.1	176.4	827	-250	0.1	6.6
Brazil	260.2		279.1	666.8	1,761	147	2.8	110.1
Cuba	1.1		8.1	26.7	48	30	0.8	21.5
Ecuador	0.8		40.6	45.7	399	-235	9.0	11.5
Guatemala	1.1		18.9	20.2	18	-6	16.3	18.1
Nicaragua	0.5		4.1	7.2	0	17	1.7	3.2
Venezuela			206.5	110.5	2,924	-1,622	0	0
Central & South America	**266.4**		**1,010.6**	**1,495.4**	**6,898**	**-849**	**214.3**	**372.6**
Austria		1.1	49.6	141.5	26	164	16.4	70.8
Belgium			48.3	233.3	13	679	28.1	129.0
Denmark		1.4	45.2	85.8	373	-211	23.1	39.5
Finland			42.6	87.3	9	217	6.5	34.3
France	14.3	6.8	299.4	960.6	81	1,632	35.7	268.5
Germany	4.6	20.3	629.6	1,179.1	155	2,114	127.1	295.8
Greece			82.0	153.8	7	375	11.9	61.2
Italy	2.6	6.3	385.1	599.7	126	1,632	13.2	19.9
Netherlands			96.5	183.2	98	932	168.1	255.7
Norway			38.6	84.2	3,334	-2,866	9.8	11.0
Portugal			47.9	110.6	4	231	0.8	11.9
Spain	5.2	0.3	190.0	587.1	24	1,132	22.3	190.9
Sweden	1.7		94.6	95.9	2	370	39.1	40.0
Switzerland			87.9	127.1	2	100	61.2	86.6
Turkey			73.0	196.2	47	478	10.4	49.2
United Kingdom		0.2	488.9	509.7	2,562	-599	50.5	63.3
Western Europe	**28.4**	**36.4**	**2,825.0**	**5,546.9**	**6,910**	**6,573**	**704.0**	**1,781.0**
Czech Republic		1.2	44.6	60.1	11	121	22.9	25.7
Lithuania		0.1	16.9	36.6	13	130	0.02	1.1
Poland	3.5		97.8	151.5	25	344	14.0	24.8
Romania			44.8	57.4	139	127	0.7	4.5
Russia	12.9		600.1	492.1	7,659	-3,831	0.02	0.1
Slovakia		0.3	17.0	21.4	4	110	7.5	5.8
Turkmenistan			17.5	20.0	195	-55	0	0
Ukraine	4.3		107.7	100.1	86	369	9.7	10.1
Uzbekistan			38.6	34.2	153	1	0	3.3
Eastern Europe & Former U.S.S.R.	**20.7**	**1.6**	**1,189.7**	**1,276.2**	**9,640**	**-3,095**	**144.2**	**178.3**

Color Codes:
Green: Countries that produce biofuels and are net importers of crude oil
Yellow: Countries that produce biofuels and are net exporters of crude oil
Orange: Countries that are net exports of crude oil with no significant biofuels production

A–2 cont. World Producers of Petroleum and Biofuels
(Thousand Barrels per Day)

	Year 2004		Year 2002					
	PRODUCTION		CONSUMPTION		PRODUCTION	IMPORTS		
	Biofuels		Motor	Diesel	Crude Oil	Crude Oil	Motor	Diesel
Country/Region:	Ethanol*	Biodiesel	Gasoline	Fuel Oil		Imports	Gasoline	Fuel Oil
Iran			296.3	431.8	3,524	-2,094	65.5	0
Iraq			79.5	128.4	2,040	-1,495	15.0	0
Kuwait			41.0	14.5	2,030	-1,138	8.0	0
Oman			18.4	18.9	899	-839	4.2	1.6
Qatar			12.7	6.7	841	-571	0	0
Saudi Arabia	5.2		256.2	402.1	8,810	-5,985	5.0	0
Syria			30.5	93.1	520	-201	0	7.9
United Arab Emirates			49.8	45.7	2,405	-1,674	0	0
Yemen			23.7	15.5	443	-342	1.1	0
Middle East	**5.2**		**912.1**	**1,283.9**	**21,561**	**-13,789**	**140.7**	**65.2**
Algeria			42.6	83.7	1,575	-868	0	0
Angola			4.2	15.8	896	-854	1.8	2.1
Cameroon			5.5	8.6	70	-45	0.5	0.9
Congo (Brazzaville)			1.0	1.5	249	-240	0	0
Congo (Kinshasa)			2.4	2.4	23	-23	2.4	2.4
Cote d'Ivoire (IvoryCoast)			3.8	7.0	19	44	0.9	1.9
Egypt			51.3	164.0	748	-140	5.5	46.2
Equatorial Guinea			0.2	0.8	213	-213	0.2	0.8
Gabon			1.1	3.7	251	-235	0.1	0.5
Kenya	0.2		9.0	12.9	0	30	5.0	8.3
Libya			44.4	59.6	1,383	-984	0	0
Mauritius	0.4		1.9	7.1	0	0	1.9	7.1
Nigeria			154.8	53.4	2,123	-1,893	94.3	1.9
South Africa	7.2		174.7	126.8	211	399	6.4	10.1
Sudan			0	2.5	240	-179	0	2.5
Swaziland	0.2		1.6	1.4	0	0	1.6	1.4
Tunisia			9.9	34.6	79	-38	3.6	27.1
Zimbabwe	0.4		7.1	11.4	0	0	5.7	11.5
Africa	**8.4**		**615.5**	**814.7**	**8,092**	**-5,050**	**198.7**	**243.4**
Australia	2.2		324.1	243.1	744	11	25.1	24.0
Brunei			4.6	3.1	189	-179	0	0
Burma			7.9	20.1	16	8	1.2	9.0
China	62.9		876.3	1,568.0	3,530	1,242	0.001	16.1
India	30.1		176.9	791.6	813	1,610	0	2.2
Indonesia	2.9		255.2	445.2	1,340	-290	54.4	147.7
Japan	2.0		1,027.9	1,212.5	120	3,987	28.8	35.4
Korea, South	1.4		175.6	402.8	3	2,157	11.9	36.7
Malaysia			154.5	161.9	795	-246	55.9	29.3
New Zealand			56.2	47.7	41	71	18.8	5.5
Pakistan	1.7		25.5	147.9	66	143	0	83.9
Papua New Guinea			1.9	10.9	55	-55	1.9	10.9
Philippines	1.4		64.1	118.6	10	258	17.6	38.5
Sri Lanka			6.5	37.3	-1	46	1.3	22.5
Taiwan			167.7	106.5	8	787	5.8	0.6
Thailand	4.8		126.2	277.2	206	675	7.5	12.2
Vietnam			47.7	82.5	340	-322	49.6	90.7
Asia & Oceania	**109.4**		**3,552.7**	**5,942.5**	**8,291**	**10,752**	**417.0**	**859.1**
World Total	**673.5**	**39.6**	**20,185.2**	**20,907.4**	**76,935**	**1,639**	**2,508.0**	**3,816.8**

Color Codes:
Green: Countries that produce biofuels and are net importers of crude oil
Yellow: Countries that produce biofuels and are net exporters of crude oil
Orange: Countries that are net exports of crude oil with no significant biofuels production

Note: (a) ethanol production includes fuel, industrial, and beverage production.

Sources: Petroleum data from U.S. Department of Energy, Energy Information Administration, "International Petroleum Consumption," www.eia.doe.gov/emeu/international/contents.html; ethanol data from F.O. Licht, cited in Renewable Fuels Association, *Homegrown for the Homeland: Industry Outlook 2005* (Washington, DC: 2005), p. 14; biodiesel data: from Christoph Berg, Senior Analyst, F.O. Licht, e-mail to Peter Stair, Worldwatch Institute, 25 January 2006.

A–3. Biofuels As a Percent of Gasoline and Diesel Consumption, by Country

(Thousand Barrels per Day or Percent if indicated)

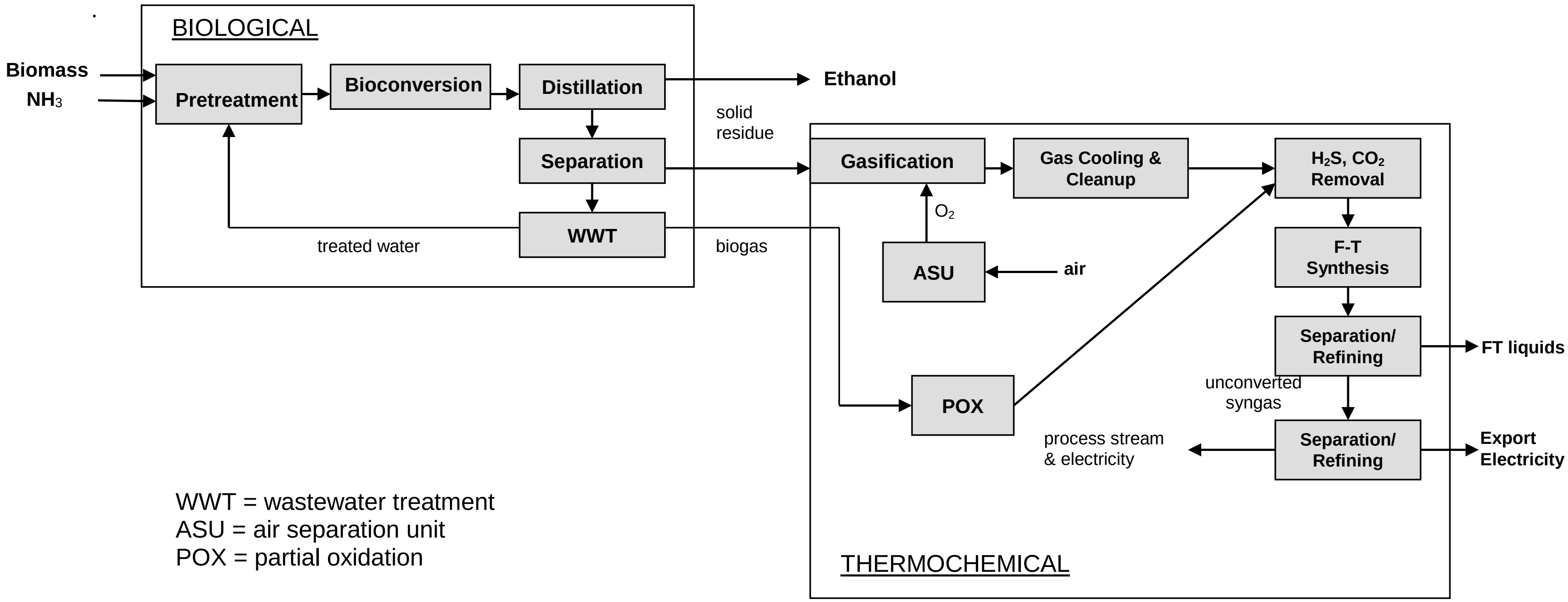
	Year 2004 PRODUCTION Biofuels		Year 2002 CONSUMPTION				
Country/Region:	Ethanol**	Biodiesel	Motor Gasoline	Diesel Fuel Oil	Ethanol % of Gasoline & Ethanol Use	Biodiesel % of Diesel & Biodiesel Use	Biofuels % of Transport Fuel Use***
Brazil	260.2		279.1	666.8	48.24%	0.00%	21.57%
Mauritius	0.4		1.9	7.1	17.39%	0.00%	4.26%
India	30.1		176.9	791.6	14.54%	0.00%	3.01%
Cuba	1.1		8.1	26.7	12.01%	0.00%	3.06%
Swaziland	0.2		1.6	1.4	11.11%	0.00%	6.25%
Nicaragua	0.5		4.1	7.2	10.95%	0.00%	4.24%
China	62.9		876.3	1,568.0	6.70%	0.00%	2.51%
Pakistan	1.7		25.5	147.9	6.25%	0.00%	0.97%
Guatemala	1.1		18.9	20.2	5.51%	0.00%	2.74%
Zimbabwe	0.4		7.1	11.4	5.35%	0.00%	2.12%
France	14.3	6.8	299.4	960.6	4.56%	0.70%	1.65%
Argentina	2.7		62.1	176.4	4.17%	0.00%	1.12%
South Africa	7.2		174.7	126.8	3.96%	0.00%	2.33%
Ukraine	4.3		107.7	100.1	3.84%	0.00%	2.03%
Thailand	4.8		126.2	277.2	3.66%	0.00%	1.18%
Poland	3.5		97.8	151.5	3.45%	0.00%	1.38%
Spain	5.2	0.3	190.0	587.1	2.66%	0.05%	0.70%
United States	230.6	1.6	8,847.8	3,775.9	2.54%	0.04%	1.81%
Kenya	0.2		9.0	12.9	2.19%	0.00%	0.91%
Philippines	1.4		64.1	118.6	2.14%	0.00%	0.76%
Russia	12.9		600.1	492.1	2.10%	0.00%	1.17%
Saudi Arabia	5.2		256.2	402.1	1.99%	0.00%	0.78%
Ecuador	0.8		40.6	45.7	1.93%	0.00%	0.92%
Sweden	1.7		94.6	95.9	1.76%	0.00%	0.88%
Indonesia	2.9		255.2	445.2	1.12%	0.00%	0.41%
Korea, South	1.4		175.6	402.8	0.79%	0.00%	0.24%
Germany	4.6	20.3	629.6	1,179.1	0.73%	1.69%	1.36%
Australia	2.2		324.1	243.1	0.67%	0.00%	0.39%
Italy	2.6	6.3	385.1	599.7	0.67%	1.04%	0.90%
Canada	4.0		680.2	484.4	0.58%	0.00%	0.34%
Japan	2.0		1,027.9	1,212.5	0.19%	0.00%	0.09%
Mexico	0.6		550.6	282.0	0.11%	0.00%	0.07%
Czech Republic		1.2	44.6	60.1	0.00%	1.96%	1.13%
Denmark		1.4	45.2	85.8	0.00%	1.61%	1.06%
Slovakia		0.3	17.0	21.4	0.00%	1.39%	0.78%
Austria		1.1	49.6	141.5	0.00%	0.77%	0.57%
Lithuania		0.1	16.9	36.6	0.00%	0.27%	0.19%
United Kingdom		0.2	488.9	509.7	0.00%	0.04%	0.02%

Color Codes:
Green: Countries that produce biofuels and are net importers of crude oil
Yellow: Countries that produce biofuels and are net exporters of crude oil

Notes: (a) Countries are ranked in this list based on the amount of ethanol produced as a percent of the gasoline demand plus ethanol produced; (b) ethanol production includes fuel, industrial, and beverage production; (c) transport fuel use includes gasoline & diesel use, plus ethanol and biodiesel production

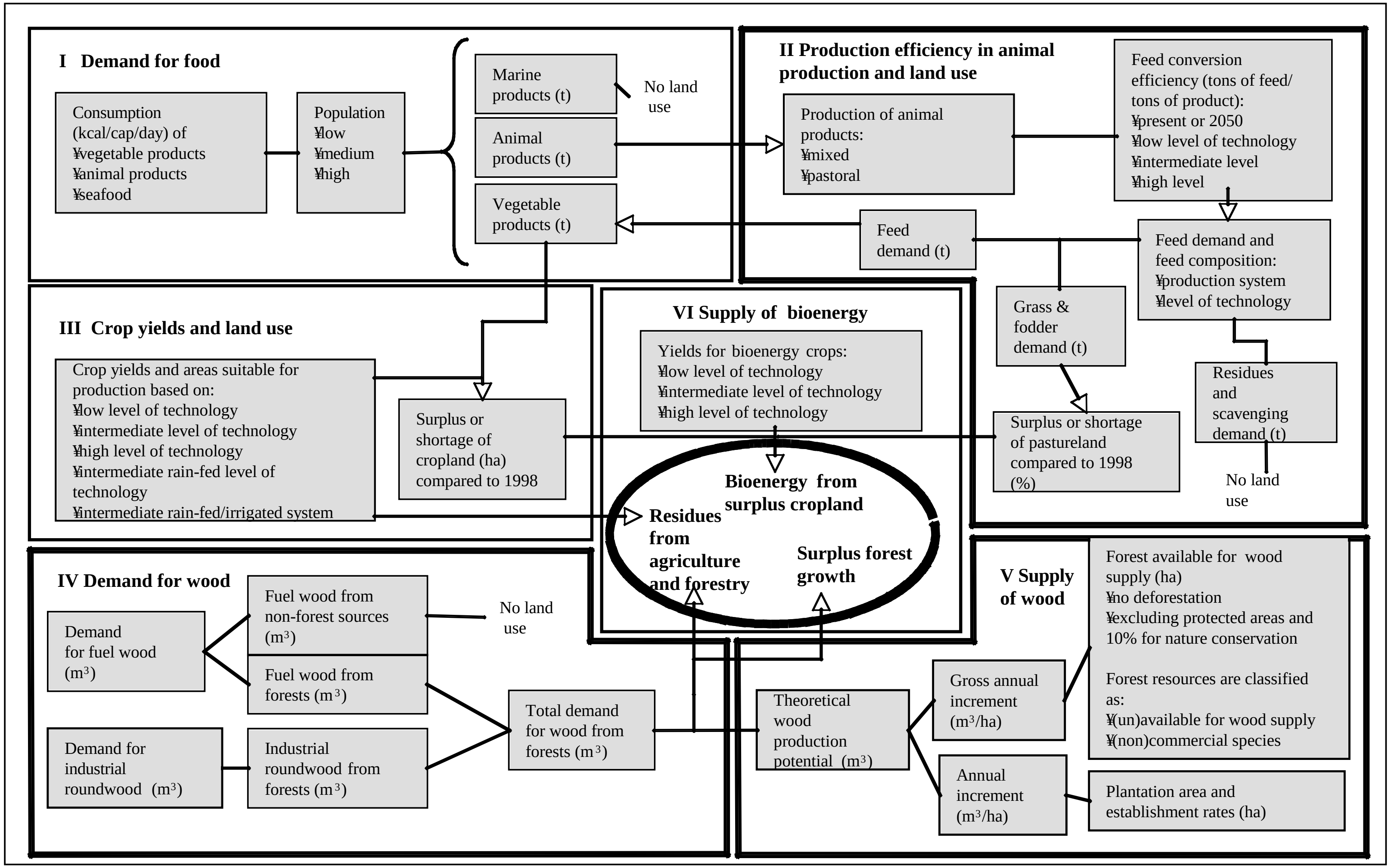
Source: Petroleum data from U.S. Department of Energy, Energy Information Administration, "International Petroleum Consumption," www.eia.doe.gov/emeu/international/contents.html; ethanol data from F.O. Licht, cited in Renewable Fuels Association, *Homegrown for the Homeland: Industry Outlook 2005* (Washington, DC: 2005), p. 14.

A–4. Block Diagram of Ethanol + F-T Fuels + GTCC



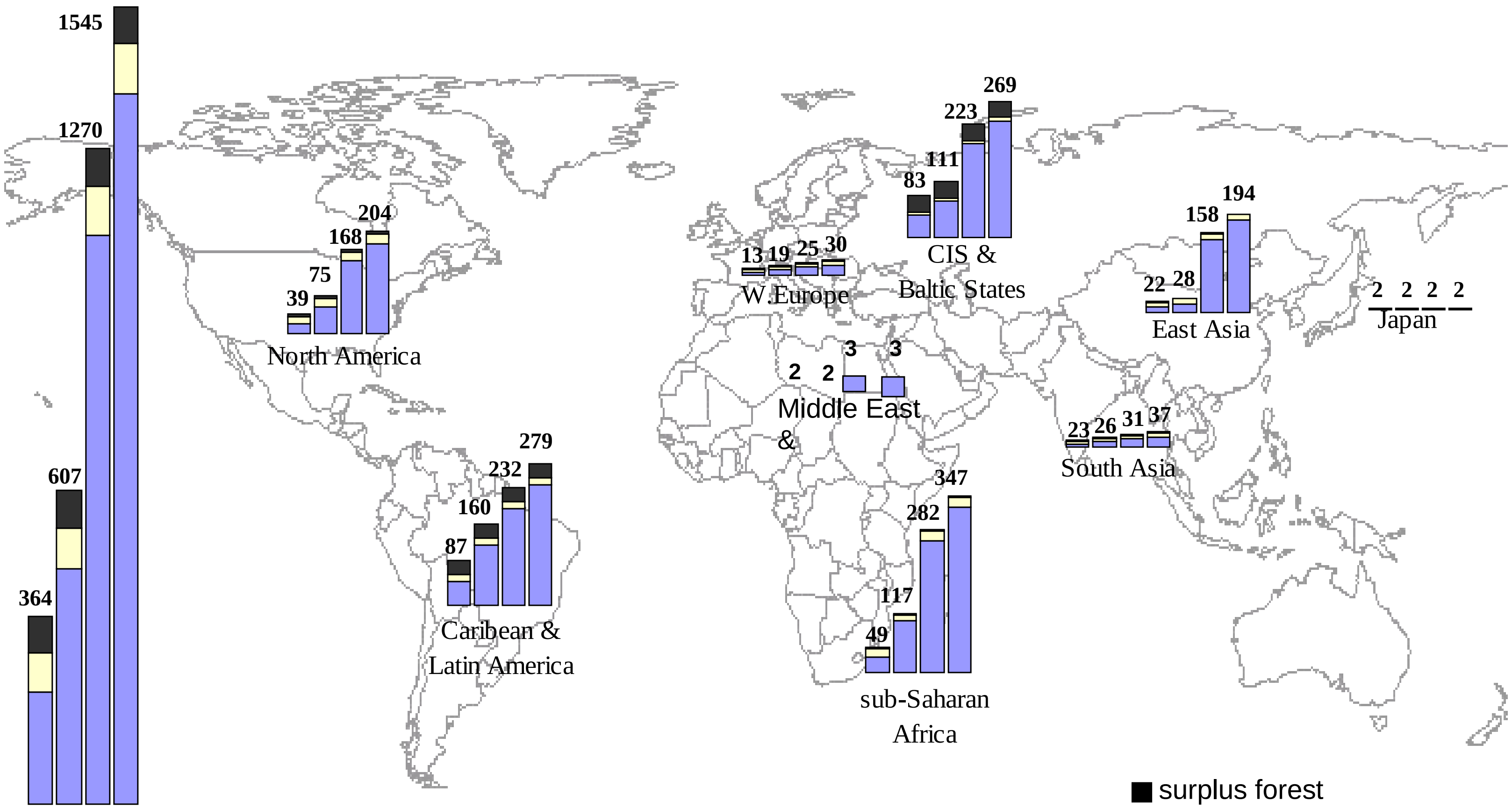
Source: Mark Laser and Lee Lynd, Thayer School of Engineering, Dartmouth College, report to Worldwatch Institute, 13 January 2006

A–5. Overview of Key Elements and Correlations Determining Bioenergy Potential



Source: Edward Smeets, Andre Faaij, and Iris Lewandowski, “A quickscan of global bioenergy potentials to 2050” (Utrecht: Copernicus Institute, Utrecht University: March 2004).

A–6. Total Potentials for Harvesting Biomass Energy in 2050, Four Scenarios



■ surplus forest

□ agricultural and forestry wastes and residues

■ dedicated woody bioenergy crops on surplus agricultural land

The four agricultural systems modeled by Smeets et. al

Factor	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Animal production system used (pastoral, mixed, landless)	Mixed	Mixed	Landless	landless
Feed conversion efficiency	High	High	High	High
Level of technology for crop production	Very high	Very high	Very high	Super high
Water supply for agriculture	Rain-fed	Irrigated	Irrigated	irrigated

Source: Edward Smeets, Andre Faaij, and Iris Lewandowski, "A quickscan of global bioenergy potentials to 2050" (Utrecht: Copernicus Institute, Utrecht University: March 2004).). Updated results obtained from the authors, March 2006

A–7. Flow Chart of Bioenergy System Compared with Fossil Reference Energy System

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Source: IEA, Bioenergy Task 38, “Standard Methodology for calculation of GHG balances” (Paris: 2006).

A–8. Selected Standards and Certification Schemes Relevant to Biofuel Production and Trade

Organization/ Scheme	Description	Web Site
General certification systems		
Clean Development Mechanism (CDM)	Approval of projects for carbon credits	cdm.unfccc.int
European Committee for Standardization (CEN)	Network of European national standards institutes providing voluntary technical standards at the European level	www.cenorm.be/cenorm/index.htm
Eco Management and Audit Scheme (EMAS)	EU voluntary instrument that acknowledges organizations that improve their environmental performance on a continuous basis.	euroa.eu.int/comm/environment/emas/index_en.org
International Standards Organization (ISO)	Network of the national standards institutes providing voluntary technical standards at the international level	www.iso.org
Certification or criteria systems for biomass energy		
European Green Electricity Network (EUGENE)	Certification system for green energy	www.eugenestandard.org
Green Gold certificate	Track and trace system for biomass developed by Essent, energy utility in the Netherlands	www.skalint.com/
Certification or criteria systems for agriculture		
EUREPGAP (EUREP-Euro-Retailer Produce Working Group)	A normative document for certification of farm products (fruits and vegetables) from integrated agriculture	www.eurep.org
EKO	Label for organic agricultural products produced according to EU Council regulation No. 2092/91	www.skal.nl
International Federation of Organic Agriculture Movements (IFOAM)	Basic international standard for organic agriculture and accreditation criteria for organic certification programs	www.ifoam.org/about_ifoam/standards/ogs.html
Sustainable Agriculture Network (SAN)	Coalition of local nonprofit conservation groups; Rainforest Alliance-certified label for bananas, coffee, cocoa, citrus, and flowers/foliage	www.rainforest-alliance.org/programs/agriculture/certification/index.html
SQF	Australian certification system for farming products; Criteria for GAP (Good Agricultural Practice) in food production	www.agriholland.nl/dossiers/kwaliteitssystemen/sqf.html

Umweltsicherungssystem (USF) (KUL)	"Environmental friendly" label for farming systems	www.tll.de//kul/kul_idx.htm
UTZ KAPEH	Certification system for fair-traded coffee; GAP guidelines for coffee	www.utzkapeh.org
Certification systems for forestry		
American Tree Farming Systems (ATFS)	Forest certification system initiated by the American Forest Foundation	www.treefarmsystem.org/cms/pages/26_19.html
Canadian Standards Association's Sustainable Forest Management Standard (CSA)	Forest certification system overseen by CSA, an independent, non-profit organization	www.Sfms.com/csa.htm/
Forest Stewardship Council (FSC)	International forest certification and chain-of-custody control system	www.fsc.org
Pan-European Forest Certification (PEFC)	Forest certification system initiated by 14 European countries and private national forest interest groups	www.pefc.org
Sustainable Forestry Initiative (SFI)	Forest certification system in the U.S. and Canada, initiated by the American Forest & Paper Association, a forest trade association	goodforests.com
Certification or criteria systems for fair trade		
Agrocel Pure& Fair Indian Organic Cotton Organization (Agrocel)	Co-ordinates the production of organic cotton and has developed criteria for fair-trade cotton chains	www.agrocel-cotton.com/english/en_home.html
AgroFair	Importer and distributor of organic and fair-trade tropical fresh fruit	www.agrofair.com
FAIRTRADE	Certification of fair-traded products	www.fairtrade.net/sites/standards/standards.html
Oxfam	Chain of shops selling 'fair' products from developing countries, with criteria for selecting partners for fair trade	www.oxfam.org/eng/pdfs/strat_plan.pdf
Sustainability criteria		
Biomass Transitie Groep	Workgroup of the Dutch Ministry of Economy developing criteria for sustainable biomass trade	
Biotrade Workshop	International Workshop 2002 discussing criteria for sustainable biomass trade	
GRAIN	Report containing criteria for sustainable biomass trade	

Greenpeace International	Environmental group with ecological criteria for sustainabiliy	www.greenpeace.org/international/campaigns/climate-change/solutions/bioenergy
International Labour Organization (ILO)	Conventions that describe acceptable labor conditions	www.ilo.org
United Nations	Conventions and Agenda 21 provide sustainability criteria for social, economic and ecological aspects	www.un.org/esa/sustdev/csd.htm
WWF	Environmental group with ccological criteria for sustainability	www.panda.org www.wwf.org
Indicator sets for Sustainable Development		
International Institute for Sustainable Development (IISD)	Indicators for sustainable development	www.iisd.org
Organisation for Economic co-operation and Development (OECD)	Indicators for sustainable development and agro-ecological indicators	www.oecd.org/home
United Nations Development Programme (UNDP)	Indicators for Sustainable Livelihoods (SL)	www.undp.org
Indicator sets for assessment of project sustainability		
UN Commission of Sustainable Development (CSD)	Method for developing sustainability indicators; indicator for sustainable development; project assessment	www.un.org/esa./sustdev/csd/csd12/csd12.htm
Gold Standard	Tool for the assessing project sustainability. Best practice benchmark for CDM and JI greenhouse gas offset projects; developed by WWF	www.panda.org/downloads/climate_change/cop8standards.pdf
World Bank	Assessment of sustainability of projects	www.worldbank.org
Guidelines for sustainable or environmental sound management		
Canadian Council of Forest Ministers (CCFM)	Set of criteria and indicators for sustainable management of Canadian forests	www.ccfm.org
Centre for International Forestry Research (CIFOR)	Criteria for sustainable forest management; manual for the developing locally adapted criteria and indicator sets	www.cifor.cigar.org/acm/pub/toolbox/html
EU Council Regulation	Definition of organic farming and principles of organic production. Certification for organic farming logo	europa.eu.int/eur/lex/lex/LexUriServ/LexUriserv.do?uri=CELEX:31991R2092:EN:HTML
Forum de l'Agriculture	Common codex for integrated farming; principles and indicator for GAP	www.farre.org/versionAnglaise/CommonCodex.htm

Raisonne Respectueuse de l'Environnement (FARRE)		
IKEA	Private company with strategy for corporate environmental and social responsibility	www.ikea.nl/ms/nl_NL/about_ikea/social/environmental/environmental.pdf
International Timber Trade Organization (ITTO)	Guidelines for the sustainable management of tropical forests; criteria for measuring sustainable tropical forest management	www.itto.or.jp/live/index.jsp
Organisation for Economic Co-operation and Development (OECD)	Guidelines for sustainable behavior of multinational enterprises	www.oecd.org
Unilever	International company that has developed GAP guidelines for sustainable agriculture	www.unilever.com
International Finance Corporation (IFC)	Guidelines for environment, health, and safety	ifcln.ifc.org/ifcest/environ.nsf/

Source: I. Lewandowski, A.W.C. Faaij, "Steps towards the development of a certification system for sustainable bio-energy trade," *Biomass and Bioenergy*, vol. 30 (2006), pp. 86–7.

GLOSSARY OF TERMS

Anhydrous ethanol. Ethanol that has less than 1 percent volume water content. Most commonly used in the United States for blending with gasoline (e.g., E10, E85); in Brazil, many vehicles are set up to run on hydrated ethanol.

ASTM D6751. A U.S. standard for biodiesel that establishes fuel quality requirements such as purity and lubricity characteristics. See CEN 14214 for European specifications.

Auto-thermal reforming (ATR). A method for extracting hydrogen from hydrocarbons. ATR breaks down hydrocarbon molecules into separate hydrogen and carbon atoms using a catalyst, steam, and oxygen.

Bxx. (where xx is a number, eg. B5, B10, etc.) Biodiesel blended with petroleum diesel, with biodiesel volume percentage indicated by the number.

Bagasse. Sugar cane processing residues.

Benzene. An aromatic hydrocarbon with a single six-carbon ring and no alkyl branches. A known carcinogen.

Biodiesel. A biofuel used in compression-ignition (diesel) engines containing mono alkyl esters of long chain fatty acids created by transesterifying plant or animal oils with a simple alcohol (typically methanol but sometimes ethanol) and a catalyst. Biofuels for diesel engines can also be produced from lignocellulosic biomass using gasification and synthesis, pyrolysis, or hydrothermal liquefaction; however, the term "biodiesel" typically applies only to those fuels derived from renewable lipid sources.

Bioenergy. Energy produced from organic matter, or biomass. Biomass may either be burned directly or converted into liquids or gaseous fuel.

Biofuels. Liquid fuels derived from organic matter, or biomass.

Biomass. Organic material from plants or animals, including forest product wastes, agricultural residues and waste, energy crops, animal manures, and the organic component of municipal solid waste and industrial waste.

Biomass power and heat. Power and/or heat generation from biomass.

Biomass residues. Residue resulting from the harvesting, processing, and use of biomass. Can be divided into primary residues (generated before and at harvest, e.g. tops and leaves of sugar cane), secondary residues (generated during processing, e.g. sugar cane bagasse, rice husks, black liquor), and tertiary residues (generated during and after product end use, e.g. demolition wood, municipal solid waste).

Biomass-to-liquid (BTL). Processes, such as gasification and Fischer-Tropsch synthesis, that convert biomass into liquid fuels.

Biorefining. The process by which biomass is converted into fuel, chemicals, and/or biomass-based materials

Biorefinery. A refining facility where biomass is converted into fuel, chemicals, materials, and other uses, all at the same plant.

Cellulosic biomass. Plant matter composed of linked glucose molecules that strengthen the cell walls of most plants. Next-generation biofuel conversion technologies can convert cellulosic biomass into liquids.

Cellulosic ethanol. Ethanol produced from cellulosic biomass, usually using acid-based catalysis or enzyme-based reactions to break down plant fibers into sugar, which is then fermented into ethanol.

CEN 14214. A standard for European biodiesel performance, established by the European Committee for Standardization, that sets fuel quality requirements such as purity and lubricity characteristics. See ASTM D6751 for U.S. standards.

Cetane number. An empirical measure of a diesel fuel's self-ignition quality that indicates the readiness of the fuel to ignite spontaneously under the temperature and pressure conditions in the engine's combustion chamber. (Higher cetane improves the performance of diesel engines.)

Clean Development Mechanism (CDM). The CDM is one of the two "flexible" financing provisions under the Kyoto Protocol. It provides opportunities to promote biofuel development in developing countries.

Combined heat and power (CHP), or cogeneration. The use of a power station to simultaneously generate both heat and electricity. It allows for more total use of energy than conventional generation, potentially reaching an efficiency of 70–90 percent, compared with approximately 50 percent for the best conventional plants.

Combustion. A chemical reaction between a compound (fuel) and an oxidizing element (oxygen in air) that releases energy in the forms of heat and light..

Compressed natural gas (CNG). Made from compressing purified natural gas (a fossil fuel composed primarily of methane) for storage in hard containers. It is frequently used to power vehicles and is considered a cleaner alternative to more carbonaceous fuels such as diesel or gasoline.

Compression-ignition engines. Also known as diesel engines. Internal combustion engines in which atomized fuel is injected into highly compressed air. The heat and pressure of the compressed air alone causes the fuel to ignite.

Consolidated bioprocessing (CBP). A strategy for processing cellulosic biomass that involves consolidating four biologically mediated events into a single step: cellulase production, cellulose hydrolysis, hexose fermentation, and pentose fermentation. This kind of processing is facilitated by microorganisms that can simultaneously hydrolyze plant fibers and starches and ferment the resulting sugars.

Corporate Average Fuel Economy (CAFE). A U.S. standard that requires light vehicles to achieve a certain average mileage per gallon (3.8 liters) of gasoline. It has been a market driver for the E85 engine.

Diesel fuel. A fuel processed from petroleum that contains a mix of molecules ranging from 12 to 22 carbon atoms (C-12 to C-22). Designed to run in diesel internal combustion engines.

Dimethyl Ether (DME). Sometimes called "methyl ether" or "wood ether." A gaseous ether (CH_3OCH_3) that can be manufactured as a biofuel and used as a substitute for natural gas.

Distillers dried grains (DDG). A co-product of dry-milling operations that produce ethanol, DDG is a fibrous, high-protein residue that can be used as food for animals, especially cattle.

Dry mill. A type of starch-ethanol mill characterized by the method of milling grains prior to fermentation into ethanol. Dried grains are ground and all parts are introduced into the production process. Proteins and fibers are usually extracted after fermentation.

Exx. (where xx is a number, e.g. E10, E20, etc.) Ethanol blended with gasoline, with ethanol volume percentage indicated by the number.

Energy crops. Crops grown and harvested for use as a feedstock in the production of fuels or other energy products. In this report, energy crops are contrasted with conventional food and feed crops. Examples include perennial grasses and short-rotation forestry species such as hybrid poplar and willow.

Ethanol. CH_3CH_2OH. A vehicle fuel typically made from fermenting sugar derived from biomass (typically corn, sugar cane, or wheat) that can replace ordinary gasoline in modest percentages (blends) in spark-ignition engines or be used in pure form in specially modified vehicles. Nearly all ethanol is produced by fermenting plant sugars and starches (or hydrolyzed cellulose or hemicellulose in the future); however, it can also be produced from fossil feedstock. In this report, ethanol refers exclusively to biomass-derived ethanol (also known as "bio-ethanol").

Ethyl ester. An alkyl ester produced by transesterfying ethanol with esters found in animal, vegetable, and waste oils; used as a biodiesel fuel.

Ethyl tertiary butyl ether (ETBE). $(CH_3)_3COC_2H$. An oxygenate blend stock formed by the catalytic etherification of isobutylene with ethanol.

Exajoule (EJ). A unit of energy equal to 10^{18} joules.

Fatty acid methyl ester (FAME). Another term for biodiesel.

Feedstock. A material used as a raw material in an industrial process.

Fischer-Tropsch (F-T) process. A biomass-to-liquid (BTL) method of synthesizing hydrocarbons, specifically gasoline and diesel molecules, from "syngas." Passes hydrogen and carbon monoxide over a catalyst, either cobalt or iron, at high temperature and pressure. Named after German chemists Franz Fischer (1877–1948) and Hans Tropsch (1889–1935), the process is most often used to create F-T diesel, a fuel for compression-ignition engines.

Flexible-fuel vehicle (FFV). A vehicle specially designed to run on straight gasoline or any gasoline-ethanol blend up to E85 in temperate climates, and E96 in tropical climates, from a single tank.

Fossil fuel equivalent (FFE). A measure of energy potential from a given fuel or energy source relative to producing that same amount of energy with fossil fuels.

Fuel atomization. A process by which fuel atomizers, such as injectors or jets, deliver fuel in minute droplets to be mixed with air prior to combustion in an engine or turbine.

Fuel Cell Vehicle (FCV). A vehicle propelled by a fuel cell engine using hydrogen as a fuel. (Note that it is possible that on-board reformers can be used to extract the hydrogen from various fuels, such as methane, gasoline, ethanol, etc.)

Fumigation. A process by which a carburetor, fuel injector, heated vaporizer, or mist generator is used to meter ethanol into a vehicle engine's air-intake manifold.

Gasification. The process of converting biomass to a mixture of carbon monoxide, carbon dioxide, hydrogen, and methane by heating it in oxygen-starved conditions. The resulting "syngas" can be used either as a fuel for heat and power production or as a feedstock for the synthesis of liquid fuels (see F-T synthesis).

Gasoline. A liquid fuel for use in internal combustion engines where the fuel–air mixture is ignited by a spark. It consists of a mixture of volatile hydrocarbons derived from the distillation and cracking of petroleum. It normally contains additives such as lead compounds or benzene to improve performance (the prevention of premature ignition) or rust inhibitors.

Gas-to-liquid (GTL). A route of gaseous fuel processing that results in byproducts that can include liquid fuels such as naphta and diesel. The resulting BTL/GTL diesel can be used as a straight fuel or blended with ordinary diesel or biodiesel.

Gas turbine (GT). An engine that passes the products of the combustion of its fuel/air mixture over the blades of a turbine. The turbine drives an air compressor, which in turn provides the air for the combustion process. The energy of the combustion products not taken up by the compressor can be used to provide a jet of exhaust gases, or drive another turbine.

Gas turbine combined cycle (GTCC). Gas-powered turbines for generating electricity that combine several components into one system to increase overall efficiency. For example, a unit may use heat from gas turbine exhaust to produce steam to turn a second turbine for two-stage power generation. Other components, such as heat recovery steam generators or peripheral electricity generators, may also be added.

General Systems of Preferences (GSP). A trade policy instrument that gives developing countries preferred access to industrialized country markets, generally through lowered tariffs.

Genetically modified (GM) crops. Plants whose genetic makeup has been altered using genetic engineering technology that does not involve natural methods of reproduction. Some biomass crops, including sugar cane and corn, have been genetically modified to improve aspects of plant productivity.

Gigajoule (GJ). A unit of energy equal to 10^9 joules.

Gigawatt (GW). A unit of power-generating capacity equal to 10^9 megawatt.

Gigawatt-hour (GWh). A unit of produced energy equal to 10^9 megawatt-hours.

Gigawatt-thermal (GWth). A unit of heat-supply capacity equal to 10^9 megawatt-thermal (MWth).

Greenhouse gas (GHG). Gaseous components of the atmosphere that contribute to the greenhouse effect of gases in the Earth’s atmosphere (where increased amounts of solar heat are trapped in the air). Human activity contributes to the greenhouse effect by releasing GHGs such as carbon dioxide, methane, and others.

Higher heating value (HHV). The amount of heat released per unit mass or unit volume of a substance when the substance is completely burned, including the heat of condensation of water vapor to liquid water.

Hydrous ethanol. Ethanol containing approximately 4 percent water by volume.

Hydrous pyrolysis. A biomass refining process that mimics the zero oxygen, pressurized, hot, and aqueous conditions that created petroleum, though in a much shorter time period. The process removes the oxygen from the biomass and yields a solid mineral layer, gaseous fuels, and a liquid “biocrude.”

Internal Combustion Engine Vehicle (ICEV). A vehicle that uses either a compression-ignition or spark-ignition engine for propulsion.

Internal rate of return (IRR). A financial measure used to evaluate the return on capital investments.

Jatropha. An oilseed crop that grows well on marginal and semi-arid lands. The bushes can be harvested twice annually, are rarely browsed by livestock, and remain productive for decades.

Joint Implementation (JI). A mechanism under the Kyoto Protocol designed to encourage GHG emissions reductions or carbon sequestration projects. The mechanism allows an Annex 1 party to implement such projects in other Annex 1 party territories in exchange for emissions reduction credits.

Joule (J). The unit of work of energy. Specifically, it is the work done or energy expended by a force of 1 newton action through a distance of 1 meter.

Kilowatt-hour (KWh). A unit of produced energy equal to 10^3 MWh.

Kilowatt-thermal (KWth). A unit of heat supply capacity equal to 10^3 MWth.

Life-Cycle Analysis (LCA). An analysis that examines the environmental impact of a product or process from its inception to the end of its useful life.

Lignocellulosic feedstock. Biomass feedstock, such as woody materials, grasses, and agricultural and forestry residues, that contains cellulose, hemicellulose, and lignin. It can be broken down in a number of ways to be used as biofuels.

Liquefied natural gas (LNG). A fossil fuel composed primarily of methane. Purified natural gas turns to liquid at -160 degrees Celsius and is 1/640th the volume of natural gas at standard temperature and pressure, making it easier to transport in specialized cryogenic tanks.

Liquefied petroleum gas (LPG). A fossil fuel extracted from crude oil and natural gas, comprised principally of propane (C_3H_8) and butane (C_4H_{10}). LPG turns to liquid under moderate pressure and is roughly 1/250th the volume of its gas form.

Lubricity. A measure of a substance's lubricating qualities, a property of oiliness or slipperiness. Lubricity is a concern for engine systems using liquid fuels, as many components, such as fuel pumps, depend upon fuel for lubrication.

Megawatt (MW), Megawatt-hour (MWh). A unit of power-generating capacity. It represents an instantaneous power flow. It is distinct from units of produced energy, i.e. megawatt-hours.

Megawatt-thermal (MWth). A unit of heat-supply capacity used to measure the potential output from a heating plant. It represents an instantaneous heat flow and should not be confused with units of produced heat (i.e., MWh(th), or megawatt-hours-thermal).

Methanol. CH_3OH. A simple alkyl also known as methyl alcohol.

Methyl ester. Another term for biodiesel.

Methyl tertiary butyl ether (MTBE). A common oxygenate added to gasoline to help combustion and reduce emissions of carbon monoxide and troposheric ozone. MTBE is highly water soluble and has been found to contaminate groundwater. The World Health Organization has identified MTBE as a carcinogen.

Miscanthus. Also known as elephant grass. A tropical and sub-tropical hardy perennial grass species that originated in Asia and Africa. It is a promising source of biomass due to its high rates of growth.

Multiple-use crops. Crops that can be used for a variety of purposes, including as human food, animal feed, material inputs for products, and energy (in the form of heat or electricity, or stored in liquid biofuels).

Municipal solid waste (MSW). Total waste excluding industrial waste, agricultural waste, and sewage sludge, including durable goods, non-durable goods, containers and packaging, food wastes, yard wastes, and miscellaneous inorganic wastes from residential, commercial, institutional, and industrial sources. Waste-to-energy combustion and landfill gas are byproducts of municipal solid waste.

Neat fuel. Fuel in its pure, unblended form.

Nitride glycol. An additive to alcohol fuels used to increase lubricity.

Nitrogen oxide (NO_x). The generic term for a group of highly reactive gases, all of which contain nitrogen and oxygen in varying amounts.

Nitrous oxide (N_2O). A nitrogen oxide that is a common pollutant from burning fossil fuels or organic matter. It is a powerful greenhouse gas and a known ozone-depleting substance

Particulate matter (PM). Fine particles of solids suspended in gas. Anthropogenic sources of aerosols originate from the burning of fossil fuels or from wind-blown dust from construction and agricultural areas. PM from petroleum sources, such as soot, are human health hazards as they may carry carcinogens.

Peroxyacetyl nitrate (PAN). An organic compound formed in the atmosphere from the addition of nitrogen dioxide, NO2, to the peroxyacyl radical formed in the oxidation of acetaldehyde. It is a component of photochemical smog and can cause irritation to the eyes and respiratory system.

Photovoltaic (PV). Photovoltaics, such as solar panels or solar cells, convert sunlight into electricity.

Poly-cyclic aromatic hydrocarbons (PAHs). A group of compounds, of which there are about 10,000, that result largely from the incomplete combustion of carbon-based materials such as fossil fuels and wood. PAHs can bond with ash and become particulate matter, irritating respiratory systems when inhaled.

Polyvinyl chloride (PVC). A hard plastic commonly used in construction and pipes. While inconclusive, some studies point to PVC as a source of carcinogenic dioxins in the environment.

Potassium hydroxide. KOH, commonly known as caustic potash, is a catalyst used with rapeseed oil in the process of transesterification to create rapeseed methyl ester (RME), a biodiesel fuel.

Proálcool. A Brazilian program launched in 1975 that aimed to reduce the country's dependence on petroleum by subsidizing the production of ethanol from sugar cane as a substitute for gasoline. The program has encouraged many technological advances and contributed to the enormous increase in Brazilian ethanol production.

Prototype Carbon Fund (PCF). The first carbon financing mechanism at the World Bank; a public-private partnership consisting of 17 companies and 6 governments.

Pyrolysis. A thermochemical process in which biomass is converted into liquid "bio-oil," solid charcoal, and light gases (H_2, CO, CH_4, C_2H_2, C_2H_4). Depending on the operating conditions (temperature, heating rate, particle size, and solid residence time), pyrolysis can be divided into three subclasses: conventional, fast, or flash.

Rapeseed. A flowering member of the Brassicacae family and a major global source of vegetable oil. Rapeseed oil is the most common feedstock for biodiesel in Europe, especially in Germany. Canola is a common North American cultivar of rape.

Rapeseed methyl ester (RME). Biodiesel made from rapeseed oil.

Reid vapor pressure (vapor pressure). The pressure exerted by the vapors released from any material at a given controlled temperature when enclosed in a laboratory vapor-tight vessel.

Renewable Fuels Standard (RFS). A regulation requiring refiners, blenders, distributors and importers to sell increasing volumes of renewable fuels—such as ethanol and biodiesel—according to an annual schedule. The U.S Energy Security Act of 2005 requires that the United States consume at least 4 billion gallons of these fuels in 2006, escalating to 7.5 billion gallons by 2012.

Renewable Transport Fuel Obligation (RTFO). A UK proposal to require that 5 percent of vehicle fuels used in the nation be derived from renewable sources by 2010.

Simultaneous saccharification and fermentation (SSF). A one-step process used to convert cellulosic biomass into alcohol that combines cellulase enzymes and microbes for fermentation. As enzymes break down cellulose into sugars, microbes ferment these sugars into alcohol.

Separate hydrolysis and fermentation (SHF). A two-step process used to convert biomass into alcohol where cellulase enzymes break down cellulose into sugars prior to the introduction of microbes for fermentation.

Short-rotation Coppice (SRC). A method of tree harvesting where the trees are harvested, and the remaining tree stumps produce vigorous regrowth that is harvested after a prescribed number of years (varying by tree species and crop management priorities); 3–4 harvests may be possible before the trees must be replanted.

Short-rotation forestry (SRF). A forest management strategy using short-rotation coppicing (or tree harvesting and replanting) after a prescribed number of years.

Short rotation woody crops (SRWC). Generally used to refer to tree crops grown with a short-rotation coppice approach.

Sodium hydroxide. NaOH, commonly known as lye. A catalyst used to transesterify oils and an alcohol into molecules of methyl ester, or biodiesel.

Soybean Methyl Ester (SME). Biodiesel derived from soybean oil.

Spark-ignition engines. Internal combustion engines that use an electronic spark from a spark plug to ignite a compressed mixture of fuel and air.

Splash blending. Blending of ethanol into gasoline or biodiesel into petroleum diesel at terminals, without active mixing.

Steam-methane reforming (SMR). A process that converts methane and light hydrocarbons to carbon monoxide and hydrogen using steam and a nickel catalyst. The reforming reactions are endothermic (they absorb heat, rather than producing heat); as a result, heat must be supplied to SMR reactors, typically by a furnace surrounding a tube bundle packed with nickel catalyst where the reforming reactions occur.

Straight vegetable oil (SVO). Known as "Pure plant oil" (PPO) in the European Union, SVO refers to either virgin or waste vegetable oils used to fuel diesel engines. While some diesel engines can run on SVO without modification, steps must be taken to address problems in colder climates, since it is generally more viscous than petrodiesel and has a higher freezing point.

Sulfur oxide (SO_x). The term for a group of compounds composed of sulfur and oxygen. SO_x, released in the burning of fuels, is a leading contributor to acid rain and can cause severe human health issues in high concentrations.

Switchgrass. A prairie grass native to North America that holds considerable promise as a feedstock for cellulosic conversion into ethanol.

Syngas (synthesis gas). A mixture of carbon monoxide, carbon dioxide, hydrogen, and methane created during the gasification process of heating biomass in the presence of air, oxygen, or steam. Syngas can be converted to a variety of fuels including hydrogen, methanol, dimethyl ether, and Fischer-Tropsch liquids.

Terawatt hour (TWh). A unit of produced energy equal to 10^{12} MWh.

Tetra-ethyl lead (TEL). An additive to gasoline introduced to reduce engine knocking and increase efficiency and octane ratings. TEL creates lead as a highly toxic pollutant in engine exhausts and has been phased out of most vehicle fuels worldwide.

Transesterification. A reaction to transform one ester into a different ester. The process used to transform natural oil into biodiesel by chemically combining the natural oil with an alcohol (such as methanol or ethanol).

Treated biogas (TB). Gas that has been treated to remove hydrogen sulfide (H_2S) and water (which can corrode fuel systems, engines, and burners).

Tree-based oilseeds. Oil seeds grown by trees, such as jatropha, that show promise as feedstock for biodiesel production.

Vinasse. The residue liquid from the distillation of ethanol, rich in potassium and organic matter. Used as a fertilizer and irrigation liquid to increase sugar cane crop yields.

Volatile organic compounds (VOCs). Organic compounds comprised of carbon and hydrogen that easily vaporize into the atmosphere. VOCs can pollute soil and groundwater, and in the presence of sunlight they react with NO_x to form tropospheric ozone, a respiratory irritant.

Volumetric Ethanol Excise Tax Credit (VEETC). U.S. legislation enacted in 2004 that establishes federal tax credits for the blending, distribution, and sale of E10, E85, and biodiesel. Each gallon of renewable fuel sold through the end of 2010 will receive a tax credit of $0.51 cents.

Well-to-wheels analysis. A life-cycle analysis of fuels that measures the efficiencies and impacts of various energy sources.

Wet mill. A type of starch-ethanol mill where grains are steeped in solutions of water and acid to break them down into separate products, such as oils, proteins, and purified starch. Wet-milling operations are more complex and generally larger than dry-milling operations, but offer a greater variety of byproducts, including high protein animal feeds, high fructose corn syrup, and biomaterial feedstock.

BIBLIOGRAPHY

ABC News Online. “North coast sugar industry to benefit from biofuels decision,” 29 November 2005.

Abengoa Bioenergy, “Abengoa Bioenegy R&D's first pilot plant is ready to begin research and development operations,” at www.abengoabioenergy.com/feature.cfm?page=6.

Abt Associates Inc., “The Particulate Related Health Benefits of Reducing Power Plant Emissions” (Bethesda, MD: October 2000), at www.abtassociates.com/reports/particulate-related.pdf.

Aden, A. et al. “Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover” (Golden, CO: National Renewable Energy Laboratory (NREL), June 2002), p. 9.

AEA Technology. “Appendix 3: Potential for Production Cost Reduction,” in *International Resource Costs of Biodiesel and Bioethanol*, prepared for the UK Department for Transport (London: 2003).

Agence de l’Environnment et de la Maîtrise de l’Energie (ADEME) and Direction des Ressources Energétiques et Minérales (DIREM), “Energy and Greenhouse Gas Balances of Biofuels’ Production Chains in France” (Paris: Ecobilan/PricewaterhouseCoopers, December 2002), at www.ademe.fr/partenaires/agrice/publications/documents_anglais/synthesis_energy_and_greenhouse_english.pdf.

Agence France-Presse. “Malaysia to Build Three Biodiesel Plants Fueled by Palm Oil,” 28 September 2005.

Agência Nacional do Petróleo e de Biocombustíveis, Superintendência de Planejamento e Pesquisa. “Volume de Petróleo Refinado nas Refinarias Nacionais (metros cúbicos),” and “Produção Nacional de Derivados de Petróleo (metros cúbicos),” 2006, at www.anp.gov.br/petro/dados_estatisticos.asp.

Ahring, B.K. et al. “Pretreatment of wheat straw and conversion of xylose and xylan to ethanol by thermophilic anaerobic bacteria,” *Bioresource Technology*, vol. 58, no.2 (1996), pp. 107–13.

“Algae—like a breath of mint for smokestacks,” *USA Today*, 10 January 2006.

Alhajji, A. F. “The Failure of the Oil Weapon: Consumer Nationalism vs. Producer Symbolism” (Ada, OH: Ohio Northern Univeristy, 2005), at www2.onu.edu/~aalhajji/ibec385/oil_weapon2.htm.

AMFI Newsletter (Advanced Motor Fuels Information), October 2005, available at http://virtual.vtt.fi/virtual/amf/pdf/amfinewsletter2005_4october.pdf.

Amoako, K.Y. Former Executive Secretary, Economic Commission for Africa, and Commissioner, Commission for Africa, presentation at Resources for Global Growth: Agriculture, Energy and Trade in the 21st Century conference, Washington, DC, 6 December 2005.

Anex, R. Associate Professor of Agricultural Systems and Bioengineering, Iowa State University, personal communication with P. Stair, Worldwatch Institute, 15 August 2005.

Apace Research Ltd, “Intensive Field Trial of Ethanol/Petrol Blend,” Energy Research and Development Council Project No. 2511 (Canberra: 1998).

Apps, P. “South Africa Maize Farmers See Ethanol Plant In 18 Months,” *Reuters*, 15 March 2005,

Arkenol. Web site, www.arkenol.com.

Armstrong, A.P. et al. “Energy and Greenhouse Gas Balance of Biofuels for Europe—an Update,” CONCAWE Report No. 2/02 (Brussels: April 2002), p. 13.

Arnold, K. et al. “Synopsis of German and European experience and state of the art of biofuels for transport,” report commissioned by the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Wuppertal: Wuppertal Institute for Climate, Energy, Environment, July 2005).

Ash, M. and E. Dohlman. “Soybeans and Oil Crops: Trade” (Washington, DC: U.S. Department of Agriculture (USDA), Economic Research Service, April 2005).

Ashworth, J. et al. *Properties of Alcohol Transportation Fuels*, prepared for U.S. Department of Energy (DOE) by Meridian Corporation (Washington, DC: May 1991).

ASSOCANA—Departamento Agrícola. “Custo Médio Operacional da Lavoura de Cana-De-Açúcar em Reais” (Assis, Brazil: 30 September 2005), at www.assocana.com.br/custo.html.

Associated Press. “Brazilian Wetlands Defender Commits Suicide in Environmental Protest,” 15 November 2005.

Associated Press. “Oil: The Flip Side,” 27 October 2004.

Atkinson, B. “The CDM, Kyoto protocol and the sugar, ethanol and biofuels industry” (Ringwood, Hampshire, UK: Agrinergy, undated), pp. 2–3.

Auto/Oil Air Quality Improvement Research Program (AQIRP), *Program Final Report*. January 1997.

Autolex Consultoria Automotiva. São Paulo, Brazil, personal communication with Alfred Szwarc, Director, ADS Tecnologia e Desenvolvimento Sustentável, São Paulo, Brazil, 2005.

autospectator.com. “Biomass-to-Ethanol Technology Could Help Replace Half of Auto Fuel in U.S,” posted 22 May 2005.

autoweb.com. “Toyota Licenses Hybrid Technology to Ford,” 25 March 2004, at http://autoweb.drive.com.au/cms/A_101177/newsarticle.html.

Azevedo, G. Director, GilTech Consultants for Technology and Sustainable Development, Brazil, e-mail to P. Stair, Worldwatch Institute, 22 November 2005.

Badger, P.C. “Ethanol from cellulose: A general review,” in J. Janick and A. Whipkey, eds., *Trends in New Crops and New Uses* (Alexandria, VA: ASHS Press, 2002), pp. 17–21.

Barrionuevo, A. “A Warning About Trade Suits Over Agriculture,” *New York Times,* 30 November 2005.

Batidzirai, B. et al., “Biomass and bioenergy supply from Mozambique,” *Energy for Sustainable Development*, March 2006, p. 10.

Battjes, J.J. “Global options for biofuels from plantations acccording to IMAGE simulations” (Groningen, The Netherlands: Rijksuniversiteit Groningen, 1994).

Baue, W. **“**ChevronTexaco Faces Class-Action Lawsuit in Ecuador Over Environmental Damage,” SocialFunds.com, 11 May 2004, at www.socialfunds.com/news/article.cgi/article1419.html.

Bauen, A. et al. “Feasibility Study on Certification for a Renewable Transport Fuel Obligation,” final report (London: Edinburgh Centre for Carbon Management, Ltd., Imperial College: June 2005).

Baumert, K.A., T. Herzog, and J. Pershing. “Navigating the Numbers: GHG Data and Climate Policy” (Washington, DC: World Resources Institute, 2005).

Bazilescu, I. and B. Lyhus, “Russia Oil Spill,” Trade and Environment Database Case Studies (Washington, DC: American University, 11 January 1997), at http://gurukul.ucc.american.edu/ted/KOMI.HTM.

Becker, K. and G. Francis. “Biodiesel from Jatropha plantations on degraded land” (Stuttgart: University of Hohenheim, 2005).

Beeman, P. “Ethanol Plans Among Iowa’s Polluters,” *Des Moines Register*, 11 September 2005.

Benbrook, C.M. “Genetically Engineered Crops and Pesticide Use in the United States: The First Nine Years,” Biotech-Info Technical Paper No. 7 (Sand Point, ID: Northwest Science and Environmental Policy Center, October 2004).

Bendz, K. “EU-25. Agriculture Situation: Pakistan, EU's second largest ethanol exporter, loses privileged status,” *GAIN Report* (Washington, DC: USDA Foreign Agricultural Service, 27 September 2005).

Bendz, K. “EU-25. Oilseeds and Products. Annual. 2005,” *GAIN Report* (Washington, DC: USDA Foreign Agricultural Service, 10 June 2005).

Bendz, K. “EU-25. Oilseeds and Products. Biofuels situation in the European Union 2005,” *GAIN Report* (Washington, DC: USDA Foreign Agricultural Service, March 2005).

Benoit, G.R. and M.J. Lindstrom. “Interpreting Tillage-Residue Management Effects,” *Journal of Soil and Water Conservation*, March-April 1987, pp. 87–90.

Bensmann, M. “Bio im Tank,” *Neue Energie*, vol. 3 (2005).

Benton, S. “Government Biofuels Strategy to Cover Multiple Benefits, Says Minister,” *Bua News*, 10 February 2006, at http://allafrica.com/stories/200602100545.html.

Berg, C. “World Fuel Ethanol Analysis and Outlook” (Ratzeburg, Germany: F.O. Licht, April 2004).

Berg, C. Senior Analyst, F.O. Licht, Agra Informa Ltd, Kent, United Kingdom, e-mail to P. Stair, Worldwatch Institute, 25 January 2006.

Bernama.com. “No Evidence of Threat to Wildlife Caused by Oil Palm Plantations,” Bernama.com (Malaysian National News Agency), 12 October 2005.

Berndes, G. et al. “The contribution of biomass in the future global energy supply: a review of 17 studies,” *Biomass and Bioenergy,* vol. 25 (2003), pp. 1–28.

Bhattacharya, P. and J. Bharati. “Strategies and Institutional Mechanisms for Large Scale Cultivation of Jatropha Curcas under Agroforestry in the Context of the Proposed Biofuel Policy of India,” abstract in *ENVIS Bulletin on Grassland Ecosystems and Agroforestry* (Indian Institute of Forest Management), December 2003, pp. 58–72.

Biewinga, E.E. and G. van der Bijl. “Sustainability of energy crops in Europe, a methodology developed an applied,” CLM 234-1996 (Utrecht: Centre for Agriculture and Environment, February 1996).

“Biomass: New Growth for Germany,” English summary brochure, at www.oeko.de/service/bio.

Blend, J. and H. Haines. “Economic Effects of Increased Ethanol Use in Montana” (Helena, MT: Montana Department of Environmental Quality, Air Energy and Pollution Prevention Bureau, 5 January 2005), at http://deq.mt.gov/Energy/bioenergy/ethanolUseInMT.asp.

Blue Sun Biodiesel. “News and Events,” at www.gobluesun.com, viewed 6 March 2006.

Bonny, S. “Why are Most Europeans Opposed to GMOs? Factors Explaining Rejection in France and Europe,” *Electronic Journal of Biotechnology*, 15 April 2003.

Bordetsky, A. et al. “Securing America: Solving our Oil Dependence through Innovation” (New York: Natural Resources Defense Council and Institute for the Analysis of Global Security, 2005).

Borjesson, P. “Environmental Effects of Energy Crop Cultivation in Sweden,” *Biomass and Bioenergy*, vol. 16 (1999), pp. 137–54.

Börjesson, P. and G. Berndes. “Multi-functional Biomass Production Systems”(Lund, Sweden; Lund University, undated).

Borlaug, N.E. “Ending World Hunger: The Promise of Biotechnology and the Threat of Anti-Science Zealotry,” *Plant Physiology*, vol. 124, no. 2 (2000), pp. 487–90.

Borough, D. “The Future of Ethanol in Europe Hinges on State Aid,” *Reuters*, 6 December 2005.

Bothast, R.J. et al. “Fermentations with new recombinant organisms,” *Biotechnology Progress*, vol. 15, no. 5 (1999), pp. 867–75.

BP. *Statistical Review of World Energy 2005* (London: 2005).

Bradsher, K. *High and Mighty*: *The Dangerous Rise of the SUV* (New York: PublicAffairs, 2002).

Bramble, B. Senior Program Advisor for International Affairs, National Wildlife Federation, e-mail to J. Sawin, Worldwatch Institute, 23 February 2006**.**

Brazilian Reference Center on Biomass (CENBIO), information obtained by A. Szwarc, União da Agroindústria Canavieira de São Paulo (UNICA), 2005.

Bridgwater, A.V. “Principles and Practice of Biomass Fast Pyrolysis Processes for Liquids,” *Journal of Analytical and Applied Pyrolysis*, vol. 51 (1999), pp. 3–22.

Brisby, S.J. Manager, Fuels Section, Stationary Source Division, California Air Resources Board, e-mail to J. Sawin, Worldwatch Institute, 1 March 2006.

British Association for Bio Fuels and Oils (BABFO). “Rationale and Economics of a British Biodiesel Industry (London: 1994), at www.biodiesel.org/resources/reportsdatabase/reports/gen/19940401_gen-294.pdf.

Brown, J. et al., “Getting on Track: Finding a Path for Transportation in the CDM,” Final report (Winnipeg, Manitoba, Canada: International Institute for Sustainable Development, December 2004), p. 16.

Brown, L.R. “New York: Garbage Capital of the World,” Eco-Economy Update (Washington, DC: Earth Policy Institute, 17 April 2002.

Brown, P. and J. Vidal. “Two GM Crops Face Ban for Damaging Wildlife,” *The Guardian*, 17 October 2003.

Brown, R. Office of Biorenewables Program, Iowa State University, “A Question of Balance,” e-mail to P. Stair, Worldwatch Institute, 30 November 2005.

Brusstar, M. and M. Bakenhus. “Economical, High Efficiency Engine Technologies for Alcohol Fuels,” U.S. Environmental Protection Agency, National Vehicle and Emissions Laboratory, XV International Symposium on Alcohol Fuels (San Diego, CA: September 2005).

Bryan, T. “Editor’s note regarding total biodiesel production capacity in the U.S.,” *Biodiesel Magazine*, October 2005;

BTG Biomass Technology Group BV. Web site, www.btgworld.com.

Buckland, H. “The Oil for Ape Scandal: How palm oil is threatening the orangutan” (London: Friends of the Earth-UK, 2004), www.foe.co.uk/resource/reports/oil_for_ape_summary.pdf.

Bugge, J. “Note: Rape Seed Oil for Transport 1: Energy Balance and CO2 Balance” (Hurup Thy, Denmark: Folkecenter for Renewable Energy, 11 September 2000), at www.folkecenter.dk/plant-oil/publications/energy_co2_balance.pdf.

Bullard, M.J., D.G. Christian, and C. Wilkins. “Quantifying Biomass Production in Crops Grown for energy,” ETSU B CR/0038-00-00 (Harwell, Didcot, Oxon: AEA Technology Environment, 1996), pp. 61–63.

Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit (BMU), “Nachhaltige Biomassenutzungsstrategien im europäischen Kontext,” at www.ie-leipzig.de/Biomassenutzung/Biomasse.htm.

Burnquist, William. Centro de Tecnologia Canavieira (CTC), Piracicaba, Brazil, conversation with Suzanne Hunt and Peter Stair, Worldwatch Institute, 24 October 2005.

Burnquist, William. CTC, Piracicaba, Brazil, conversation with Suzanne Hunt and Peter Stair, Worldwatch Institute, 28 October 2005.

Burton, G.W. “Improved recurrent restricted phenotypic selection increases bahiagrass forage yields,” *Crop Science,* vol. 22 (1982), pp. 1058–61;

Burton, G.W. and B.G. Mullinix. “Yield distributions of spaced plants within Pensacola bahiagrass populations developed by recurrent restricted phenotypic selection,” *Crop Science*, vol. 38 (1988), pp. 333–36, cited in Nathanael Greene et al., “Growing Energy: How Biofuels Can Help End America’s Oil Dependence” (Washington, DC: Natural Resources Defense Council, December 2004), p. 26.

Burton, John. “Malaysia Likely to Legislate Biofuel Use,” *Financial Times*, 7 October 2005.

Bushuk, W. “Rye Production and Uses Worldwide,” *Cereal Foods World*, vol. 6, no. 2 (2005).

Business Wire. “Corn Wet Milling Industry Faces Many Challenges in Current Global Environment, Says New Analysis,” 13 January 2006.

California Air Resources Board. “Toxic Air Contaminants, Staff Report/Executive Summary” (Sacramento: 20 November 2004, at arbis.arb.ca.gov/toxics/summary/summary.htm, cited in Nathanael Greene et al., “Growing Energy: How Biofuels Can Help End America’s Oil Dependence” (Washington, DC: Natural Resources Defense Council, December 2004), pp. 49–51.

Calzoni, J. et al. “Bioenergy for Europe: Which Ones Fit Best? A Comparative Analysis for the Community,” Funded by the European Commission in the framework of the FAIR Programme (Heidelberg: Institute for Energy and Environmental Research, November 2000).

Cannell, Melvin. “Carbon Sequestration,” presentation at “The Biofuels Directive: Potential for Climate Protection?” European Climate Forum, 3rd Autumn Conference, Tyndall Centre, University of East Anglia, Norwich, UK, 8–10 September 2003.

Carneiro de Miranda, R. Winrock International, e-mail to P. Stair, Worldwatch Institute, 16 February 2006.

Carvalho, L.C.C. and U. A. Alegre. “Brazil-State of Ethanol Industry,” Presentation at 1st World Summit on Ethanol for Transportation, Quebec, Canada, 2–4 November 2003.

Center for Science in the Public Interest. “Cruel Oil: How Palm Oil Impacts Health, Rainforest and Wildlife” (Washington, DC: May 2005).

Centre for International Economics. “Impact of Ethanol Policies on Feedgrain Users in Australia,” prepared for MLA on behalf of the Australian Beef Industry (Canberra and Sydney: August 2005).

Changing World Technologies. Web site, at www.changingworldtech.com, viewed 12 January 2006.

Chippewa Valley Ethanol Company and Frontline Bioenergy LLC. “CVEC Announces Alliance with Frontline BioEnergy, LLC,” press release (Ames, IA and Benson, MN: 12 December 2005).

Choren Industries. Web site, www.choren.de.

Clanton, B. “Large SUVs lose luster, cost big 3,” *The Detroit News,* 18 January 2005.

Clay, J. Vice President, Center for Conservation Innovation, World Wildlife Fund, presentation at Resources for Global Growth: Agriculture, Energy and Trade in the 21st Century conference, Washington, DC, 6 December 2005.

Clay, J. *World Agriculture and Environment* (Washington, DC: Island Press, 2004), p. 412.

Clean Air Task Force et al. “Prevention of Air Pollution from Ships: Reducing Shipping Emissions of Air Pollution—Feasible and Cost-Effective Options,” submitted by Friends of the Earth International to the Marine Environment Protection Committee, International Maritime Organization, 7 April 2005, Annex, pp. 4–8.

“Coconut-Biodiesel for All Government Vehicles, Memorandum Circular 55,” PowerPoint presentation, Energy Center (Manila: 30 June 2004).

Coelho, S.T. “Biofuels—Advantages and Trade Barriers,” presentation at the United Nations Conference on Trade and Development, Geneva, 4 February 2005.

Collier, R. “Fueling America: Oil’s Dirty Future—Canadian Oil Sands: Vast Reserves Second to Saudi Arabia Will Keep America Moving, But at a Steep Environmental Cost,” *San Francisco Gate*, 22 May 2005.

Colorado Environmental Coalition et al. “Oil Shale and Tar Sands Resources Leasing Programmatic EIS; Scoping Comments,” comments submitted to the U.S. Bureau of Land Management, Argonne National Laboratory, 31 January 2006, pp. 18–43.

Commission of the European Communities, “Green Paper: A European Strategy for Sustainable, Competitive and Secure Energy” (Brussels: 2006), p. 16.

Commonwealth of Australia Biofuels Taskforce. “Report of the Biofuels Taskforce to the Prime Minister” (Barton, ACT: August 2005), p. 63

Conservation Technology Information Center (CTIC). “Conservation Tillage and Other Tillage Types In the United States–1990-2004,” *National Crop Residue Management Survey*, at www.ctic.purdue.edu/Core4/CT/CT.html.

Conway, G. and G. Toennisessen. “Feeding the World in the Twenty-First Century,” *Nature*, December 1999, pp. C55–C58.

Cook, J. and J. Beyea. “An Analysis of Environmental Impacts of Energy Crops in the USA: Methodologies, Conclusions and Recommendations” (Washington, DC: National Audubon Society, undated), at www.panix.com/~jimcook/data/ec-workshop.html, viewed 18 July 2005.

Copulos, M.R. “America's Achilles Heel—The Hidden Costs of Imported Oil” (Washington, DC: National Defense Council Foundation, October 2003).

Copulos, M.R. “Economic, Security and Environmental Impacts of Alternative Fuel and Automotive Technologies. A Cost/Benefit Analysis of the Clean Cities Program” (Washington, DC: National Defense Council Foundation, 2005), p. 9.

Core, J. “New Method Simplifies Biodiesel Production,” *Agricultural Research*, April 2005.

Corpuz, P.G. “Philippines Oilseeds and Products. GRP Promotes Biodiesel Use 2004,” *GAIN Report* (Washington, DC: U.S. Department of Agriculture (USDA) Foreign Agricultural Service, 3 May 2004).

Council for Biotechnology Information. “Answers to frequently asked questions about biotech biofuels,” at www.whybiotech.com/index.asp?id=5035, viewed 25 December 2005.

Couto, L. and D.R. Betters, “Short Rotation Eucalypt Plantations in Brazil: Social and Environmental Issues” (Oak Ridge, TN: Oak Ridge National Laboratory, February 1995).

Cullen, D. “Biggest Study of GMO Finds Impact on Birds, Bees,” *Reuters*, 22 March 2005.

Cullen D. “UK Gene Crop Test Results Fuel Demands for Ban,” *Reuters*, 17 October 2003.

Cunha, Fernando. “A Logística Atual de Transporte das Distribuidoras e a Infra-Estrutura para Exportação de Álcool,” presentation at Álcool: Potencial Gerador de Divisas e Empregos seminar, O Banco Nacional de Desenvolvimento Econômico e Social (BNDES), 25–26 August 2003, at www.bndes.gov.br/conhecimento/publicacoes/catalogo/s_alcool.asp

Czernik, S. and A.V. Bridgwater. “Overview of Applications of Biomass Fast Pyrolysis Oil,” *Energy & Fuels*, vol. 18 (2004), pp. 590–98.

D1 Oils Plc. Web site, www.d1plc.com.

D1 Oils Plc. “D1 Oils biodiesel land reclamation project launched in the Philippines,” press release (London: 5 May 2005).

D1 Oils Plc. “South Africa—Biodiesel is a National Priority,” at www.d1plc.com/global/africa_south_africa.php, viewed 3 March 2006.

D1 Oils Plc. “The Birth of a Global Biodiesel Business,” at www.d1plc.com/about/history.php, viewed 12 March 2006.

Damen, K. and A. Faaij. “A Life Cycle Inventory of Existing Biomass Import Chains for ‘Green Electricity’ Production,” prepared for Essent Energy (Utrecht: Copernicus Institute, Department of Science, Technology and Society, Utrecht University, January 2003).

Dammer, T. Office of Naval Petroleum and Oil Shale Reserves, US DOE, “Strategic Significance of America’s Oil Shale Resource,” presentation at 2005 Energy Information Agency Midterm Energy Outlook Conference, Washington, DC, 12 April 2005, available at www.eia.doe.gov/oiaf/archive/aeo05/conf/pdf/dammer.pdf.

Daoudi, M.S. and M.S. Dajani, “The 1967 Oil Embargo Revisited” *Journal of Palestine Studies*, vol. 13, no. 2 (1984), pp. 65–90;

Darmouth College and Natural Resources Defense Council. “The Role of Biomass in America’s Energy Future (RBAEF),” sponsored by US DOE, the Energy Foundation, and the National Commission on Energy Policy, project Web site at http://engineering.dartmouth.edu/other/rbaef/index.shtml.

de La Hamaide, S. “French to Boost Biofuel Output to Meet EU Target,” *Reuters*, 14 June 2005.

de Oliveira, N. “Neither FTAA Nor EU. WTO Is Brazil's Only Hope,” *Brazil Magazine,* 5 November 2004.

De La Torre Ugarte, D. “The Contribution of Bioenergy to a New Energy Paradigm” (Knoxville, TN: Agricultural Policy Analysis Center, University of Tennessee, 2005), p. 1.

De La Torre Ugarte, D. et al. “The Economic Impacts of Bioenergy Crop Production on U.S. Agriculture,” Agricultural Economic Report Number 815 (Washington, DC: USDA, February 2003).

de Vasconcelos, J.N. “Continuous Ethanol Production Using Yeast Immobilized on Sugar Cane Stalks,” *Brazilian Journal of Chemical Engineering*, July/September 2004.

Delucchi, M.A. “A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials. Documentation of Methods and Data” (Davis, CA: Institute of Transportation Studies (ITS), University of California at Davis, December 2003);

Delucchi, M.A. “A Multi-Country Analysis of Lifecycle Emissions from Transportation Fuels and Motor Vehicles” (Davis, CA: ITS, University of California at Davis, May 2005).

Delucchi, M.A. “Conceptual and methodological issues in lifecycle analyses of transportation fuels” (Davis, CA: ITS, University of California at Davis, 2004).

Delucchi, M.A. Research Scientist, ITS, University of California at Davis, e-mails to J. Sawin, Worldwatch Institute, 10 March and 13 March 2006.

Dent, H. “China: Where has all the oil gone? IEA wonders,” PetroleumWorld.com, 8 December 2005.

Desai, S.G., M.L. Guerinot, and L.R. Lynd. “Cloning of L-lactate dehydrogenase and elimination of lactic acid production via gene knockout in Thermoanaerobacterium saccharolyticum,” *Applied Microbiology and Biotechnology*, vol. 65, no. 5 (May 1999), pp. 600–05.

Dessus, B. et al. “World Potential of Renewable Energies: Actually Accessible in the Nineties and Environmental Impact Analysis” (Paris: 1992).

Deurwaarder, E.P. “Overview and Analysis of National Reports on the EU Biofuel Directive: Prospects and Barriers for 2005,” Sixth Research Framework Programme of the European Union (Petten, The Netherlands: Energy Research Centre of the Netherlands, May 2005), p. 25.

Deutsche Union zur Förderung von Oel- und Proteinpflanzen e.V. (UFOP). *Statusbericht Biodiesel – Biodieselproduktion und Vermarktung in Deutschland 2005* (Berlin: 2005).

Devi, L., K.J. Ptasinski. and F.J.J.G. Janssen. “A review of the primary measures for tar elimination in biomass gasification processes,” *Biomass and Bioenergy*, vol. 24 (2003), pp.125–40.

Devine, T.E. and E.O. Hatley. “Registration of ‘Donegal’ Forage Soybean,” *Crop Science*, vol. 38 (1998), pp. 1719–20.

Devine, T.E., E.O. Hatley, and D.E. Starner. “Registration of ‘Derry’ Forage Soybean,” *Crop Science*, vol. 38 (1998), p. 1719.

Devine, T.E., E.O. Hatley, and D.E. Starner. “Registration of ‘Tyrone’ Forage Soybean,” *Crop Science*, vol. 38 (1998), p. 1720.

Devine, T.E. and J.E. McMurtrey III. “Registration of “Tara” Soybean,” *Crop Science*, vol. 44 (2004), p. 1020.

Dhuyvetter, K.C., T.L. Kastens, and M. Boland. “The U.S. Ethanol Industry: Where will it be located in the future?” newsletter (Davis, CA: University of California, Agricultural Issues Center, November 2005), p. i.

Dias De Oliveira, M. E., B.E. Vaughan, and E.J. Rykiel Jr. “Ethanol as Fuel: Energy, Carbon Dioxide Balances, and Ecological Footprints,” *BioScience*, July 2005, p. 601.

Dickerson, M. “Brazil’s Ethanol Effort Helping Lead to Oil Self-Sufficiency,” *Los Angeles Times*, 17 June 2005.

Dinjus, E. and A. Kruse. “Hot compressed water—a suitable and sustainable solvent and reaction medium?” *J. Phys.: Condens. Matter*, vol. 16 (2004), pp. S1161–69.

Dobermann, A. et al. “Understanding and Managing Corn Yield Potential,” in Proceedings of the Fertilizer Industry Round Table, Charleston, SC, 28-30 October 2002 (Forest Hill, MD: The Fertilizer Industry Round Table).

Dobson, A. “The Kennedy Administration and Economic Warfare against Communism,” *International Affairs*, vol. 64, no. 2 (1988), pp. 599–616.

Doggett, T. “EPA Seeks to Ease US Ethanol Plant Pollution Rules,” *Reuters*, 3 March 2006.

Domac, J., K.M. Richards, and V. Segon. “Old fuel for modern times. Socio-economic drivers and impacts of bioenergy use” (Paris: International Energy Agency Bioenergy Task 29, 2005), p. 8, at www.iea-bioenergytask29.hr/pdf/Domac_Richards_Segon_2005.pdf.

Doniger, D. “Oil Companies, Making Record Profits, Seek Environmental Rollbacks” (New York: Natural Resources Defense Council, 8 May 2001).

Dornburg, V. and A.P.C. Faaij. “Cost and CO2 -Emission Reduction of Biomass Cascading: Methodological aspects and case study of SRF Poplar,” *Climatic Change*, vol. 71, no. 3 (2005), pp. 373–408.

Dornburg, V., J. van Dam, and A. Faaij. “Estimating GHG emission mitigation supply curves of large scale biomass use on a country level,” *Biomass & Bioenergy*, September 2004.

dos Santos, M.A. "Energy Analysis of Crops Use for Producing Ethanol and CO_2 Emissions" (Rio de Janeiro: Energy Planning Program, COPPE/UFRJ, Cidade Universitária, undated), at www.ivig.coppe.ufrj.br/doc/alcofoen.pdf.

Downstream Alternatives Inc. "Infrastructure Requirements for an Expanded Fuel Ethanol Industry" (Oak Ridge, TN: Oak Ridge National Laboratory Ethanol Project, January 2002).

Duffy, M. Associate Professor of Economics, Iowa State University, e-mails to P. Stair, Worldwatch Institute, 2 December 2005.

Duffy, M. Associate Professor of Economics, Iowa State University, "Where is the Profit?" presentation at Southeast Research and Demonstration Farm Annual Meeting, Ames, IA, 4 March 2004.

Duffy, M. Associate Professor of Economics, Iowa State University, "The Changing Structure of Agriculture," presentation at Independent Insurance Agents of Iowa Rural Agents Conference (Ames, IA: 26 January 2006).

Dukes, J.S. "Burning Buried Sunshine: Human Consumption of Ancient Solar Energy," *Climatic Change*, vol. 6, no. 1-2 (2003), pp. 31–44.

Durbin, T. et al., "Final Report: Effects of Ethanol and Volatility Parameters on Exhaust Emissions," CRC Project No. E-67, prepared for Coordinating Research Council, Inc., Alpharetta, GA (Riverside, CA: College of Engineering, Center for Environmental Research and Technology, University of California, 30 January 2006), pp. 47–48.

Dutch Energy Agency (NOVEM) and Arthur D. Little (ADL), *Analysis and Evaluation of GAVE Chains*, Vol. 1–3 (Utrecht: GAVE Analysis Programme, December 1999).

DynaMotive Energy Systems Corporation Web site, www.dynamotive.com.

Earley, J., T. Earley, and M. Straub. "Specific Environmental Effects of Trade Liberalization: Oilseeds" (Washington, DC: International Policy Council for Food and Agriculture, October 2005), p. 5.

Easterly, J. Easterly Consulting, e-mail to S. Hunt, Worldwatch Institute, 4 March 2006.

Easterly, J. Easterly Consulting, personal communication with P. Stair, Worldwatch Institute, March 2006.

Econbrowser. "What's up with oil prices," 4 June 2005, at www.econbrowser.com/archives/2005/06/whats_up_with_o.html.

Edmons, J.A. et al. "Agriculture, land use, and commercila biomass energy: A preliminary integrated analysis of the potential role of biomass energy for reducing future greenhouse related emissions" (Richland. WA: Pacific Northwest National Laboratory, 1996).

Edwards, R. et al. "Well-to-wheel analysis of future automotive fuels and power trains in the EU context, well-to-tank report" (Brussels: CONCAWE, EUCAR, 2003), p. 25.

Edwards, R. "Updated WTW Analysis of Biomass-Based Transport Fuels," PowerPoint presentation, Joint Research Centre, European Commission, Paris, 2005, slide 32.

Ejigu, M. "The Biofuels Option, The Way Ahead: Some Thoughts,' presentation at International Energy Agency Conference, Paris, 20–21 June 2005.

Elsayed, M.A., R. Matthews, and N.D. Mortimer. "Carbon and Energy Balances for a Range of Biofuels Options," report prepared for UK Department of Trade and Industry Sustainable Energy Programmes (Sheffield, UK: Sheffield Hallam University, March 2003).

Elsbett. Web site, www.elsbett.com.

Energetics and NEOS Corporation, “Economic Impact of Ethanol Production Facilities: Four Case Studies,” prepared for Western Regional Biomass Energy Program and Great Lakes Regional Biomass Energy Program (Golden, CO and Chicago: June 1994).

Energetics, Inc., “Energy and Environmental Profile of the U.S. Petroleum Refining Industry,” report prepared for US DOE (Washington, DC: US DOE, Office of Industrial Technologies, 1998).

“Energy Oil and Palm,” *The Rams Horn: Journal of Food Systems Analysis*, January 2006.

Environment News Service. “Brazil Embraces Alternative Energy,” 19 August 2005.

Environment News Service. “Brazil’s New National Park Protects Vanishing Savannah,” 15 December 2005.

Environment News Service. “Illinois Ethanol Producer Must Install Air Pollution Controls,” 24 December 2005.

Environment News Service. “Minnesota Aims to Be Saudi Arabia of Renewable Fuels,” 18 May 2005.

Environmental Defense, “Oil Refining-Main Page,” www.environmentaldefense.org/article.cfm?ContentID=1537, posted 4 May 1999.

Environmental Working Group. “Top Subsidies in the US 1995-2004,” Farm Subsidy Database, at www.ewg.org/farm/region.php?fips=00000, viewed 27 January 2006.

Epstein, P. R. and J. Selber, eds. “Oil: A Life Cycle Analysis of its Health and Environmental Impacts” (Cambridge, MA: The Center for Health and the Global Environment, Harvard Medical School, Harvard University, March 2002).

Esipisu, M. “Gene Crops No Help to Africa So Far—Report,” *Reuters*, 11 January 2006.

European Biomass Industry Association. “Biodiesel,” *Biofuels for Transport*, at http://p9719.typo3server.info/214.0.html, viewed 12 March 2006

European Commission (EC). “An EU Strategy for Biofuels,” Communication from the Commision (Brussels: 7 February 2006).

EC. “An EU Strategy for Biofuels,” draft final (Brussels: 2006).

EC. “Annex to the Communication from the Commission: An EU Strategy for Biofuels, Impact Assessment” Commission Staff Working Document (Brussels: 2006), p. 17.

EC, “Application of biologically derived products as fuels or additives in combustion engines” (Brussels: Directorate-General XII Science, Research and Development: 1994).

EC. “Biomass Electricity—Technical Development Status” (Brussels: 2006), at http://europa.eu.int/comm/energy_transport/atlas/htmlu/bioetech.html.

EC. “Commission Staff Working Document, Annex to the Communication from the Commission: An EU Strategy for Biofuels, Impact Assessment”.

EC. “Commission Urges Luxembourg, Italy, Portugal and Slovakia to Implement Biofuels Directive,” press release (Brussels: 13 December 2005).

EC. “Commission Urges New Drive to Boost Production of Biofuels,” press release (Brussels: 8 February 2006).

EC. “Directive 2003/30/CE of the European Parliament and Council on 8 May 2003 relative to the promotion of the utilization of biofuels or of other renewable fuels in transportation,” L 123/42 PT (Brussels: 8 May 2003).

EC. “Directive 2003/30/EC, 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport, O.J. L123, 17/05/2003” (Brussels: 2003).

EC. “Directive 2003/96/EC, 27 October 2003 restructuring the Community framework for the taxation of energy products and electricity, O.J. L283, 31/10/2003” (Brussels: 2003).

EC. Directorate-General for Energy and Transport. “Promoting Biofuels in Europe: Securing a Cleaner Future for Transport” (Brussels: 2004).

EC. “External Costs: Research Results on Socio-Environmental Damages Due to Electricity and Transport” (Brussels: 2003).

EC. “EU Biomass Action Plan” (Brussels: 7 December 2005), p. 34.

EC. “EU Radically Reforms Its Sugar Sector to Give Producers Long-term Competitive Future,” press release (Brussels: 24 November 2005).

European Environment Agency (EEA), “How much biomass can Europe use without harming the environment?” EEA Briefing (Copenhagen: 2005).

European Environment Agency Topic Centre on Air Emissions and Climate Change (EEA-ETC/ACC) cited in Peter Taylor, “Transport Emission Trends in Europe,” presentation at “The Biofuels Directive: Potential for Climate Protection?” European Climate Forum, 3rd Autumn Conference, Tyndall Centre, University of East Anglia, Norwich, UK, 8–10 September 2003.

F.O. Licht’s World Ethanol and Biofuels Report. “Australia aims to exceed biofuel targets,” 4 January 2006.

F.O. Licht’s World Ethanol and Biofuels Report. “Australia’s Queensland sees ethanol sector as sugar saviour,” 26 September 2005.

F.O. Licht’s World Ethanol and Biofuels Report. “Biofuels and the international development agenda,” 11 July 2005.

F.O. Licht’s World Ethanol and Biofuels Report. “Biofuels to ease economic pain,” 7 October 2005.

F.O. Licht’s World Ethanol and Biofuels Report. “Commission cuts sugar quotas for 2006/07,” 8 March 2006.

F.O. Licht’s World Ethanol and Biofuels Report. “Domestic fuel ethanol program proposed,” 25 July 2005.

F.O. Licht’s World Ethanol and Biofuels Report. “Ethanol to have mixed impact on US agriculture,” 9 November 2005.

F.O. Licht’s World Ethanol and Biofuels Report. “EU Approves French-Dutch Biodiesel JV,” 7 October 2005.

F.O. Licht’s World Ethanol and Biofuels Report. “German winter rapeseed plantings rise on biodiesel demand,” 3 February 2006.

F.O. Licht's World Ethanol and Biofuels Report. “Malaysia to boost palm oil output by 25% by 2010,” 27 January 2006.

F.O. Licht's World Ethanol and Biofuels Report. “Petrobras eyes ethanol pipeline with Goias,” 3 February 2006.

F.O. Licht’s World Ethanol and Biofuels Report. “Rapeseed prices continue to climb on EU biodiesel demand,” 14 February 2006.

F.O. Licht's World Ethanol and Biofuels Report, “Rising ethanol prices may hit Brazilian flex-fuel car sales,” 9 March 2006.

F.O. Licht’s World Ethanol and Biofuels Report. “Soaring sugar prices unsettle Brazilian ethanol market,” 7 February 2006.

F.O. Licht’s World Ethanol and Biofuels Report, “Soaring sugar prices unsettle ethanol market,” 20 February 2006.

F.O. Licht’s World Ethanol and Biofuels Report. “Sugar Exports May Hit New Low,” 1 December 2005.

F.O. Licht’s World Ethanol and Biofuels Report. “The rest of the world,” 9 November 2005;

F.O. Licht’s World Ethanol and Biofuels Report. “USDA raises corn use estimate for fuel ethanol production,” 8 March 2006.

F.O. Licht’s World Ethanol and Biofuels Report, “World ethanol production 2005 to be higher than expected,” 24 October 2005.

F.O. Licht’s World Ethanol and Biofuels Report, 24 October 2005.World ethanol production 2005 to be higher than expected.

Faaij, A. Associate Professor and Coordinator Research Energy Supply & System Studies, Copernicus Institute, Utrecht University, the Netherlands, e-mails to S. Hunt, Worldwatch Institute, 3 March and 10 March 2006.

Faaij, A. Copernicus Institute, Utrecht University, report submitted to Worldwatch Institute, 17 January 2005.

Faaij, A. “Bioenergy in Europe: Changing Technology Choices,” *Energy Policy*, 5 December 2003.

Faaij, A. “Modern Biomass Conversion Technologies,” *Mitigation and Adaptation Strategies for Global Change*, draft accepted for publication, 2005.

Faaij, A. and A. Walter, “Findings of the meeting,” presentation at the Workshop and Business Forum on Sustainable Biomass Production for the World Market, organized by IEA Task 40 Sustainable Bioenergy Trade, Tasks 30 and 31, University of Campinas, São Paulo, Brazil, November 2005.

Faaij, A. et al. “Biomass potential assessment in Central and Eastern European countries and opportunities for the Ukraine” (Utrecht: Copernicus Institute, Utrecht University, January 2005).

Faaij, A. et al., “Characteristics and availability of biomass waste and residues in the Netherlands for gasification,” *Biomass and Bioenergy*, vol. 12, no. 4 (1997), pp. 225–40.

Faaij, A., A. Wierczorek, and M. Minnesma. “International Debate on International Biotrade,” summary of international workshop, Amsterdam, The Netherlands, September 2002.

Faaij, A., A. Wieczorek, and M. Minnesma. *International debate on international biotrade; International Workshop Report,* Office of Inter-Human Dimensions Programme – Industrial Transformation (IHDP-IT), the Department of Science, Technology and Society - Utrecht University and Institute for Environmental Studies - Free University of Amsterdam (Utrecht: NOVEM, April 2003).

Faaij, A.P.C. “Bio-energy in Europe: Changing Technology Choices,” *Energy Policy* (Special Issue on Renewable Energy in Europe), February 2006, pp. 322–42.

Faaij, A.P.C. et al. “Mondiale beschikbaarheid en mogelijkheden voor import van biomassa voor energie in Nederland: Synthese van het onderzoeksproject GRAIN: Global Restrictions on Biomass Availability for Import to the Netherlands” (Utrecht: Vakgroep Natuurwetenschap & Samenleving, University of Utrecht, July 2000).

Farrell, A.E. et al. “Ethanol Can Contribute to Energy and Environmental Goals,” *Science*, 27 January 2006, pp. 27–29.

“Fast–Tracking a ‘Feasible’ EU-Mercosur Agreement: Scenarios for Untying the Agricultural Knot,” draft prepared for the “Working Group on EU-Mercosur Negotiations” of the Mercosur Chair of Sciences Po, Paris, presented at a workshop at the Faculty of Law, Barcelona, Spain, 29 March 2004.

Figueres, C. “Policies and Programs under the CDM,” 2005, at http://lists.iisd.ca:81/read/attachment/28306/1/Policies%20and%20programs%20under%20the%20CDM.pdf.

Filho, A.B. Director, AgroEnergy Program, Brazilian Ministry of Environment, “The AgriEnergy Option for the Future,” presentation at the Workshop and Business Forum on Sustainable Biomass Production for the World Market, São Paulo, Brazil, 30 November–2 December 2005.

Fischer, G. and L. Schrattenholyer. “Global bioenergy potentials through 2050,” *Biomass and Bioenergy*, vol. 20 (2000), pp. 151–59.

Flavin, C. “Fossil Fuel Use Surges,” in Worldwatch Institute, *Vital Signs 2005* (New York: W.W. Norton & Company, 2005) pp. 30–31.

Food and Agricultural Policy Research Institute. “Implications of Increased Ethanol Production for U.S. Agriculture” (Columbia, MO: University of Missouri-Columbia, August 2005).

Forest Stewardship Council (FSC). Web site, www.fsc.org.

FSC. “About FSC,” at www.fsc.org/en/about/about_fsc.

FSC. “FSC Principles and Criteria for Forest Stewardship” (Bonn: April 2004).

FSC. “Policy and Standards,” at www.fsc.org/en/about/policy_standards.

Freeman, S. and A. Joyce. “Ford to Cut 14 Plants and Up to 30,000 Jobs—N. American Auto Division Lost $1.6 Billion in 2005,” *Washington Post*, 24 January 2006.

Friends of the Earth-UK, “Leaked WTO report: US misled the world on ‘victory,’” press release (London: 28 February 2006).

Friends of the Earth-UK. “The Oil for Ape Scandal: How Palm Oil is Threatening the Orang-utan (London: September 2005), p. 9.

Fritsche, U. Öko-Institut, Darmstadt, Germany, e-mails to S. Hunt, Worldwatch Institute, 8 March and 13 March 2006..

Fritsche, U. Öko-Institut, Darmstadt, Germany, reviewer comments, 9 March 2006.

Fritsche, U. et al. “Stoffstromanalyse zur nachhaltigen energetischen Nutzung von Biomasse,” final report for the German Federal Ministry for the Environment (Darmstadt/Berlin/Freiburg: 2004).

Fritsche, U.R., K. Hünecke, and K. Wiegmann. “Criteria for Assessing Environmental, Economic, and Social Aspects of Biofuels in Developing Countries,” report commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ) (Freiburg: Öko-Institut e.V., February 2005), p. 32.

Fulton, L. “Biofuels for Transport: An International Perspective,” presentation at Conference of the Parties (COP)-10 for the UN Framework Convention on Climate Change, International Centre for Trade and Sustainable Development (ICTSD)/UNCTAD, Argentina, 14 December 2004.

Lew Fulton, “Driving Ahead: Biofuels for Transport Around the World,” *Renewable Energy World*. July-August, pp. 180–89.

Fulton, L. Sustainable Transport, Division of Global Environment Facility Coordination, United Nations Environment Programme, e-mail to P. Stair, Worldwatch Institute, July 2005.

Fulton, L. et al. *Biofuels For Transport: An International Perspective* (Paris: International Energy Agency, April 2004).

Gallegeher, P. “Biomass Feedstock Composition and Property Database” (Washington, DC: USDOE: January 2006), at www1.eere.energy.gov/biomass/feedstock_databases.html.

Gardner, B. “Fuel Ethanol Subsidies and Farm Price Support: Boon or Boondoggle?”(College Park, MD: University of Maryland Department of Agricultural and Resource Economics, October 2003).

Gardner, T. “Can Fungi Trim the US Gasoline Habit?” *Reuters*, 27 February 2006.

Garsten, E. “High gas prices scare of the sales of SUV’s: Automakers depend on big vehicle sales for pumping up the bottom line,” *The Detroit News*, 15 March 2005.

Gastellum, J. Energy Future Coalition, personal communication with Ladeene Freimuth, Freimuth Consulting, January 2006.

Gehua, W. et al. “Liquid Biofuels for Transportation: Chinese Potential and Implications for Sustainable Agriculture and Energy in the 21st Century,” report prepared for GTZ (Beijing: 2005).

Genencor International. “Genencor Celebrates Major Progress in the Conversion of Biomass to Ethanol,” press release (Palo Alto, CA: 21 November 2004).

Genencor International. “Transforming the Ethanol Industry” (Palo Alto, CA: June 2005).

General Agreement on Tariffs and Trade. Article III: 4.

General Motors et al. ”GM Well-to Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicles Systems – A European Study; ANNEX – Full Background Report” (Ottobrunn, Germany, 2002), at www.lbst.de/gm-wtw.

German Federal Institute for Geosciences and Natural Resources (BGR**),** “Total known potential of conventional petroleum,” www.bgr.bund.de/cln_030/nn_468074/EN/Home/homepage__node.html__nnn=true, viewed 28 April 2006**.**

Gerpen, J., D. Clements, and G. Knothe. “Biodiesel Production Technology: August 2002—January 2004” (Golden, CO: National Renewable Energy Laboratory, June 2004).

Gerrard, S. et al. “Drill Cuttings Piles in the North Sea: Management Options During Platform Decommissioning,” Research Report 31 (Norwich, UK: Centre for Environmental Risk, University of East Anglia, 1999).

Girard, P., A. Fallot, and F. Dauriac. “Biofuels Technology: State-of-the-Art,” prepared for the Global Environment Facility (UNEP/GEF) Technical Workshop on Liquid Biofuels, New Delhi, India, 29 August–1 September 2005.

“Global Bioenergy Partnership White Paper,” prepared by the Italian Ministry for the Environment and Territory with the participation of Imperial College London, Itabia and E4tech, October 2005.

Global Environment Facility, Small Grants Program. “Climate Change,” at http://sgp.undp.org/index.cfm?module=ActiveWeb&page=WebPage&s=foCC, viewed December 2005.

Goldemberg, J. and I. Macedo. “Brazilian Alcohol Program: An Overview,” in International Energy Agency, *Energy for Sustainable Development* (Paris: May 1994).

Goldemberg, J. et al. “How adequate policies can push renewables,” *Energy Policy*, 22 February 2003.

Goodman, M. QSS Group, e-mail to S.C. Trindade, SE2T International, Ltd., 22 February 2006.

Gover, M.P. et al. “Alternative Road Transport Fuels—A Preliminary Life-Cycle Study for the UK,” ETSU Report R92 Volumes 1 & 2 (Oxford: Energy Technology Support Unit, 1996).

Government of Germany. “Report of the Fuel Matrix Working Group” (Berlin: 2004), p. 18 *(in German)*.

Government of Manitoba, Ministry of Energy, Science and Technology. “Energy Initiatives: Ethanol Blended Fuels” (Manitoba: 2003), at www.gov.mb.ca/est/energy/initiatives/ ethanolfuels.html.

Government of the Philippines. “DOE identifies alternative fuel sources (Philippines)” (Manila: 26 August 2005), at www.pia.gov.ph/news.asp?fi=p050826.htm&no=16.

Graham, R.L., L.L. Wright, and A.F. Turhollow. “The Potential for Short-Rotation Woody Crops to Reduce U.S. CO2 Emissions,” *Climatic Change*, vol. 22 (1992), pp. 223–238, cited in R.L. Graham, W. Liu, and B.C. English. “The Environmental Benefits of Cellulosic Energy Crops at a Landscape Scale,” in *Environmental Enhancement through Agriculture: Proceedings of a Conference*, Tufts University, Boston, MA, 15–17 November 1995.

Graham, R.L., W. Liu, and B.C. English. “The Environmental Benefits of Cellulosic Energy Crops at a Landscape Scale,” in *Environmental Enhancement through Agriculture: Proceedings of a Conference*, Tufts University, Boston, MA, 15–17 November 1995.

Green Car Congress. “Coconut Biodiesel Blend Hits Local Philippine Market,” 13 August 2005, www.greencarcongress.com/2005/08/coconut_biodies.html.

Green Car Congress. “EarthFirst Importing Biodiesel to US; Soy Lobby Reacts,” 14 November 2006, at www.greencarcongress.com.

Green Car Congress. “Malaysia to Mandate B5 Biodiesel in 2008,” 6 October 2005, at www.greencarcongress.com/2005/10/malaysia_to_man.html;

Green Car Congress. “Petrobras Forms Ethanol Joint Venture in Japan,” 19 December 2005, at www.greencarcongress.com/2005/12/petrobras_forms.html.

GreenBiz.com. “Researchers Explore Climate-Friendly Farming,” 27 June 2005.

Greene, N. et al. *Growing Energy: How Biofuels Can Help End America’s Oil Dependence* (Washington, DC: Natural Resources Defense Council, December 2004).

GreenFuel Technologies Corporation. Web site, www.greenfuelonline.com/index.htm.

Haines, H. Montana Department of Natural Resources, personal communication with Worldwatch Institute, 14 December 2005.

Haley, S. and N.R. Suarez. “Sugar and Sweeteners Outlook” (Washington, DC: U.S. Department of Agriculture, 2004), at http://usda.mannlib.cornell.edu/reports/erssor/specialty/sss-bb/2004/sss241.pdf.

Hall, D.O. et al. “Biomass for Energy: Supply Prospects,” in B.J. Johansson et al., eds., *Renewables for Fuels and Electricity* (Washington, DC: Island Press, 1993).

Halweil, B. “Where Have All the Farmers Gone?,” *World Watch*, September/October 2000, p. 17.

Hamelinck, C.N. “Outlook for Advanced Biofuels” (Utrecht: Utrecht University, 7 June 2004).

Hamelinck, C.N. and A.P.C. Faaij. “Future Prospects for Production of Methanol and Hydrogen from Biomass,” *Journal of Power Sources*, vol. 111 (2002), pp. 1–22.

Hamelinck, C.N. and A.P.C. Faaij. “Outlook for Advanced Biofuels,” *Energy Policy*, article in press, 2006 (provided by A. Faaij).

Hamelinck, C.N., R.A.A. Suurs, and A.P.C. Faaij. “International Bioenergy Transport Costs and Energy Balance,” *Biomass and Bioenergy*, vol. 29, no. 2 (2005), pp. 114–34.

Hamilton, J.D. “Oil and the Macroeconomy Since World War II,” *Journal of Political Economy*, vol. 91, no. 2 (1983), pp. 228–48.

Hammel-Smith, C. et al. “Issues Associated with the Use of Higher Ethanol Blends (E17-E24)” (Golden, CO, NREL: October 2002), pp. ii, 11–12.

HART Downstream Energy Services. “Ethanol Market Fundamentals,” report to The New York Board of Trade (New York: 9 March 2004).

Hearn, K. “Buenos Bios, How South American Biofuels are Gaining Steam, and Why that Freaks the U.S. Out,” *Grist Magazine*, 15 December 2005.

Heaton, E.A. et al. “Miscanthus for Renewable Energy Generation: European Union Experience and Projections for Illinois” (Champaign, IL: University of Illinois at Urban-Champaign, October 2003), p. 13.

Heckeroth, S. “Toward Sustainable Agriculture” (Albion, CA: 1999), at www.renewables.com/Permaculture/SustAgri.htm, viewed 25 December 2005.

Heisner, R. BC International, conversation with P. Stair, Worldwatch Institute, 24 August 2005.

Henke, J. *Biokraftstoffe – eine weltwirtschaftliche Perspektive* (Kiel: Institut für Weltwirtschaft, 2005).

Henke, J., G. Klepper, and J. Netzel. *Tax Exemption for Biofuels in Germany: Is Bio-Ethanol Really an Option for Climate Policy?* Kieler Arbeitspapiere 1136 (Kiel: Institut für Weltwirtschaft, 2002), p. 17.

Hess, M.A. et al. “The Effect of Antioxidant Addition on NOx Emissions from Biodiesel,” *Energy and Fuels*, 17 March 2005, pp. 1749–54.

Hettenhaus, J. “Talking about corn stover with Jim Hettenhaus,” in *The Carbohydrate Economy* (Minneapolis, MN: Institute for Local Self-Reliance, Summer 2002).

Himmel, M.E. et al. “Advanced Bioethanol Production Technologies: A Perspective,” *ACS Symposium Series*, vol. 666 (1997), p. 45.

Hin, H. “Ford Launches Ethanol-compatible Car,” *Mail & Guardian* online, 27 October 2005.

Ho, N.W.Z., Z. Chen, and A.P. Brainard. “Genetically engineered Saccharomyces yeast capable of effective cofermentation of glucose and xylose,” *Applied and Environmental Microbiology*, vol. 64, no. 5 (1998), pp. 1852–59.

Hodes, G.S., B.E. Utria, and A. Williams. “Ethanol: Re-examining a Development Opportunity for Sub-Saharan Africa,” draft for review (Washington, DC: The World Bank Group, September 2004).

Hogan, M. “German Biodiesel Sales Strong as Oil Prices Rise,” *Reuter*s, 19 August 2005.

Hollenbacher, R. “Biomass Combustion Technologies in the United States,” paper presented at the Biomass Combustion Conference, Reno, NV, 28–29 January 1992.

Hoogwijk, M. “On the global and regional potential of renewable energy sources” (Utrecht: Utrecht University, 2004).

Hoogwijk, M. et al. “Exploration of the ranges of the global potential of biomass for energy,” *Biomass and Bioenergy*, vol. 25, no. 2 (2003), pp. 119–33.

Howse, R. “Post-Hearing Submission to the International Trade Commission: World Trade Law and Renewable Energy: The Case of Non-Tariff Measures” (Vienna: Renewable Energy and International Law Project, 5 May 2005), p. 16.

Howse, R. and E. Tuerk. “The WTO Impact on Internal Regulations: A Case Study of the *Canada-EC Asbestos* Dispute,” in G. Bermann and P.Mavroidis, eds., *Trade and Human Health and Safety* (New York: Cambridge Univ. Press, 2006), pp. 77–117.

Howse, R. and E. Tuerk. “The WTO Impact on Internal Regulations—A Case Study of the Canada-EC Asbestos Dispute: in G. de Búrca and J. Scott, eds., *The EU and the WTO: Legal and Constitutional Issues* (Oxford: Hart Publishing, 2001), pp. 283–328.

Hunt, S. and J. Sawin, with P. Stair. “Cultivating Renewable Alternatives to Oil,” in Worldwatch Institute, *State of the World 2006* (New York: W.W. Norton & Company, 2006), p. 73.

Hunt, S. “Notes from Workshop and Business Forum on Sustainable Biomass Production for the World Market,” organized by IEA Task 40 Sustainable Bioenergy Trade, Tasks 30 and 31, University of Campinas, São Paulo, Brazil, November 2005 (Washington, DC: 2005);

Hutchinson-Jafar, L. “Oil-Stung Caribbean Looks at Energy Alternatives,” *Reuters*, 18 January 2006.

Hwang, R. Vehicle Policy Director, Natural Resources Defense Council, San Francisco, CA, e-mail to J. Sawin, Worldwatch Institute, 12 March 2006.

Illovo Suga. “World of Sugar: International Sugar Statistics,” 2005, awww.illovo.co.za/worldofsugar/internationalSugarStats.htm, viewed 12 March 2006.

Ingram, L.O. et al. “Enteric bacterial catalysts for fuel ethanol production,” *Biotechnology Progress*, vol.15, no.5 (1999), pp. 855–66.

Ingram, L.O. et al.”Metabolic engineering of bacteria for ethanol production,” *Biotechnology and Bioengineering*, vol. 58, no. 2–3 (1998), pp. 204–12.

Institute for Agriculture and Trade Policy, Trade and Governance Program. “CAFTA’s Impact on U.S. Ethanol Market” (Minneapolis, MN: June 2005).

Institute Francais Riera, “Panorama 2004: A Look at Biofuels in Europe” (Lyon: 2004).

Interacademies, “Transgenic Plants and World Agriculture,” report prepared under the auspices of Seven Academies of Science (Brazil, China, India, Mexico, Third World, UK, US) (Washington, DC: 2000).

Intergovernmental Panel on Climate Change (IPCC). *Special Report on Emission Scenarios* (Cambridge: 2000).

IPCC, Working Group III. *IPCC Third Assessment Report, Climate Change 2001: Mitigation* (Cambridge University Press: 2001).

International Centre for Trade and Sustainable Development (ICTSD), “Can London Deliver What Hong Kong Couldn’t?” *Bridges Weekly Trade Digest,* January-February 2006.

ICTSD. “EU Releases Reform Plan for Sugar,” *Bridges Weekly Trade Digest*, 29 June 2005.

ICTSD. “WTO Environment Committee Drafts Text for Hong Kong,” *Bridges Weekly Trade Digest,* 16 November 2005.

International Energy Agency (IEA). *World Energy Outlook 2004* (Paris: 2004).

IEA. “Analysis of the Impact of High Oil Prices on the Global Economy” (Paris: May 2004), p. 2.

IEA. “Greenhouse Gas Balances of Bioenergy Systems” (Paris: IEA Bioenergy Task 25, 1998).

IEA. “Standard Methodology for calculation of GHG balances” (Paris: Bioenergy Task 38, 2006).

IEA. “Sustainable Production of Woody Biomass for Energy,” a position paper prepared for IEA Bioenergy (Paris: 2002).

International Federation of Organic Agriculture Movements. “The IFOAM Organizational Structure,” at www.ifoam.org/about_ifoam/inside_ifoam/organization.html, viewed 10 March 2006.

International Fund for Agricultural Development. “IFAD Strategic Framework for 2002-2006” (Rome: March 2002).

International Policy Council for Food and Agricultural Trade. “A look at the EU’s proposed sugar reforms,” (Washington, DC: 2005), at www.agritrade.org/Publications/EU%20Sugar %20Reform.pdf.

International Sugar Organization. *ISO Sugar Yearbook 1999* (London: 1999);

Iogen Corporation. Web site, at www.iogen.ca.

Isla, P.A.A. “RP, Thailand agree on regional biofuel standard,” *The Manila Times*, 1 September 2004.

Joensen, L. and S. Semino, “Argentina’s Torrid Love Affair with the Soybean,” *Seedling* (GRAIN), October 2004 (excerpt from Lilian Joensen, Stella Semino, and Helena Paul, “Argentina: Case Study on the Impact of RoundUp Ready Soya” (Brighton, UK: Rural Reflection Group, Argentina and EcoNexus, UK, March 2005)).

Johansson, T.B. et al. “A renewables-intensive global energy scenario (appendix to chapter 1),” in T.B. Johansson et al., eds., *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993), pp. 1071–43.

Johnson, F. Stockholm Environment Institute, e-mail to S. Hunt, Worldwatch Institute, 14 February 2006.

Jones, C. “Europe Adopts Biodiesel: Can an African Bean Crack Europe’s Biodiesel Blockage?” *EcoWorld*, 28 September 2005

Jordan, J. and Associates. “Ethanol: Prospectus: World Markets for Fuel Ethanol” (Houston, TX: September 2005).

Journey to Forever. “Vegetable Oil Yields,” at www.journeytoforever.org/biodiesel_yield.html, viewed 16 May 2005.

Juniger, M. and A. Faaij. “IEA Bioenergy Task 40: Country Report for the Netherlands” (Paris: International Energy Agency Task 40, Sustainable International Bioenergy Trade, July 2005, p. 23, at www.senternovem.nl/mmfiles/IEA_Task_40_Country_Report_NL_tcm24-152474.pdf.

Kaltner, F.J. et al. “Liquid Biofuels for Transportation in Brazil: Potential and Implications for Sustainable Agriculture and Energy in the 21st Century,” prepared for Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Rio de Janeiro: Fundação Brasileira para o Desenvolvimento Sustentável, November 2005).

Kaltschmitt, M., C. Rosch, and L Dinkelbach, eds. “Biomass Gasification in Europe,” prepared for the European Commission (Stuttgart: Institute of Energy Economics and the Rational Use of Energy (IER), University of Stuttgart, October 1998).

Kaltschmitt, M. et al. “Analyse und Bewertung der Nutzungsmöglichkeiten von Biomasse–Arbeitspaket des IE Leipzig,” In Vorbereitung (Leipzig: 2005), p. 18.

Karekezi, S. “Renewable Energy Technologies in sub-Saharan Africa," presentation to Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ, 19 April 1995.

Karekezi, S. et al. “Traditional Biomass Energy: Improving its Use and Moving to Modern Energy Use,” Thematic Background Paper (Bonn: Renewables 2004, January 2004).

Karpenstein-Machan, M. “Konzepte für den Energiepflanzenbau – Perspektiven eines pestizidfreien Anbaus von Energiepflanzen zur thermischen Verwertung im System der Zweikulturnutzung” (Frankfurt: DLG-Verlag, 1997).

Kartha, S., G. Leach, and S. Chella Rajan. “Advancing Bioenergy for Sustainable Development. Guideline for Policymakers and Investors. Volumes I, II, and III” (Washington, DC: World Bank Energy Sector Management Assistance Program, April 2005).

Keeney, D. and S. Suppan, Institute for Agriculture and Trade Policy (IATP), comments provided in J. Kleinschmit, IATP, e-mail to J. Sawin, Worldwatch Institute, 21 February 2006.

Kerssen, M. and R.H. Berends. “Life Cycle Analysis of the HTU Process” (Apeldoom, The Netherlands: Dutch Research Organization for Environment, Energy and Process Innovation, 2005), at www.novem.nl/default.asp?menuId=10&documentId=115819.

Khosla, V. “Biofuels: Think Outside the Barrel,” presentation to Center for American Progress, 10 January 2006, at www.khoslaventures.com/presentations/Biofuels_Dec2005.v3.2.ppt.

Kim, S. and B.E. Dale. **“**Allocation Procedure in Ethanol Production System from Corn Grain,” *International Journal of Life Cycle Assessment*, vol. 7 (2002), p. 237.

Kinast, J.A. “Properties of Biodiesels and Biodiesel/Diesel Blends,” prepared by Gas Technologies Institute for NREL (Golden, CO: March 2003).

Klein, K. et al. “Ethanol Policies, Programs and Production in Canada,” PowerPoint Presentation, Center for Research in the Economics of Agrifood, Laval University, Ste. Foy, Quebec, Canada, at www.farmfoundation.org/projects/documents/klein-ethanol.ppt, viewed 6 March 2006.

Knight, P. “New Flex-Fuel Engines Transform Consumer Options in Brazil,” *F.O. Licht’s World Ethanol and Biofuels Report*, 23 July 2003.

Kojima, M. and Johnson, T. “Potential for Biofuels for Transport in Developing Countries” (Washington, DC: World Bank, October 2005)

Kovarik, B. “Henry Ford, Charles Kettering and the ‘Fuel of the Future,’” *Automotive History Review*, Spring 1998, pp. 7–27, at www.radford.edu/~wkovarik/papers/fuel.html.

Krahl, J. et al. “Comparison of biodiesel with different diesel fuels regarding exhaust gas emissions and health effects,” 2001, available at www.ufop.de/downloads/Biodiesel_comparison.pdf.

Krishnan, B. and S. Mohanty, “Commodities - Bullish Palm Looks to Biofuel for Future,” *Reuters*, 23 February 2006.

Kyodo News. “Brazil’s Petrobras to Sell Ethanol in Japan,” 20 December 2005.

Larsen, R. et al. “Might Canadian Oil Sands Promote Hydrogen Production for Transportation? Greenhouse Gas Emission Implications of Oil Sands Recovery and Upgrading.” paper submitted to *World Resource Review* (Chicago: Center for Transportation Research, Argonne National Laboratory, December 2004).

Larson, E.D. “Liquid Biofuel Systems for the Transport Sector: A Background Paper,” draft for discussion at the Global Environment Facility Scientific and Technical Advisory Panel Workshop on Liquid Biofuels, New Delhi, 29 August–1 September 2005.

Laser, M. Research Associate, Thayer School of Engineering, Dartmouth College, e-mail to J. Easterly, Easterly Consulting, 2 March 2006.

Laser, M. and L. Lynd. Thayer School of Engineering, Dartmouth College, report to Worldwatch Institute, 13 January 2006.

Lashof, D.A. and D.A. Tirpak, eds. “Policy options for stabilizing global climate” (New York: Hemisphere Publishing Corprations, 1990).

Lazarus, M. et al. “Towards a Fossil Free Energy Future” (Boston: Stockholm Environmental Institute, 1993).

Leemans, R. et al. “The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source,” *Global Environmental Change*, vol. 6, no. 4 (1996), pp. 335–57.

Leighton, F.A. “Petroleum Oils and Wildlife” (Saskatoon, SC: Canadian Cooperative Wildlife Health Centre, Western College of Veterinary Medicine, University of Saskatchewan, May 2000), at http://wildlife1.usask.ca/ccwhc2003/wildlife_health_topics/oil/oil1.php.

Lemley, B. “Anything into Oil,” *Discover*, May 2003.

Lepach, A.J. “Perspectivas Futuras Para o Etanol Combustível. Etanol CombustívelÇ Balanço e Perspectivas,” Evento Comemorativo dos 30 Anos da Criação do Proálcool, 16–17 November 2005, Auditório da Faculdade de Ciências Médicas, University of Campinas, Campinas, Brazil, at www.nipeunicamp.org.br/proalcool/Palestras/17/Andre%20j.ppt.

Lewandowski, I. and A. Faaij. “Steps Towards the Development of a Certification System for Sustainable Bio-Energy Trade,” FAIR Biotrade project (Utrecht: Copernicus Institute of Sustainable Development and Innovation, July 2004).

Levelton Engineering Ltd. “Engineering Assessment of Net Emissions of Greenhouse Gases from Ethanol –Gasoline Blends in Southern Ontario” (Richmond, BC: January 2000), at www.tc.gc.ca/programs/Environment/climatechange/docs/ETOH-FNL-RPTAug30-1999.htm.

Levy, R.H. “Les biocarburants. Report to the French Government based on figures from the Commission Consultative pour la Production des Carburants de Substitution” (Paris: 1993).

Lima Verde Leal, M.R. Pesquisador Associado, e-mail to P. Stair, Worldwatch Institute, 2 December 2005.

Lima Verde Leal, M.R. University of Campinas, personal communication with S.C. Trindade, SE2T International Ltd., 26 December 2005.

Liu, D. “Chinese Development Status of Bioethanol and Biodiesel,” presentation at “Biofuels: An Energy Solution,” 2005 World Biofuels Symposium, Tsinghua University, Beijing, 13–15 November 2005.

Lobell, D.B. and G.P. Asner. “Climate and Management Contributions to Recent Trends in U.S. Agricultural Yields,” *Science*, 14 February 2003, p. 1032.

Lorenz, D. and D. Morris, “How Much Energy Does It Take to Make a Gallon of Ethanol?” (Washington, DC: Institute for Local Self Reliance, August 1995).

Lovins, A. et al. *Winning the Oil Endgame* (Snowmass, CO: Rocky Mountain Institute, 2005), p. 2.

Lynd, L.R. et al. “Bioenergy: Background, Potential, and Policy” (Washington, DC: Center for Strategic and International Studies, 2003).

Lynd, L.R. et al. “Consolidated Bioprocessing of Lignocellulosic Biomass: An Update,” *Current Opinion in Biotechnology*, vol. 16 (2005), pp. 577–83.

Lyon, N. “Taxation of on-farm biodiesel favouring fossil fuels,” *The Land* (New South Wales, Australia), 13 October 2005.

Lyons, H.A., S.G. Anthony, and P.A. Johnson. “Impacts of increased poplar cultivation on water resources in England and Wales,” *Aspects of Applied Biology*, vol. 65 (2001), pp. 83–90.

Macedo, I. University of Campinas (UNICAMP), Campinas, São Paulo, Brazil, personal communication with S.C. Trindade, 27 December 2005.

Macedo, I.C. “Fuel Ethanol Production in Brazil,” in *Proceeding of the First Biomass Conference of the Americas*, Burlington, Vermont, August 1993 (Golden, CO: NREL, 1993), pp. 1185–93.

Macedo, I.C. et al. “Sugar Cane’s Energy: Twelve Studies on Brazilian Sugar Cane Agribusiness and Its Sustainability” (São Paulo: União da Agroindústria Canavieira de São Paulo, September 2005).

Macedo, I.C., R. Lima Verde Leal, and J. Silva, “Perspectivas de un Programa de Biocombustibles en América Central, Proyecto Uso Sustentable de Hidrocarburos, Comisión Económica para América latina y el Caribe” (Economic Commission for Latin America: 2004), at www.eclac.org.mx.

Mali-Folkecenter, “The Jatropha Plant as a Tool for Combating Desertification, Poverty Alleviation, & Provision of Clean Energy Services to Local Women” (Bamako, Mali: May 2004).

Mandal, R. “The Indian Biofuels Programme—National Mission on Bio-diesel,” presentation at the International Conference and Expo, Biofuels 2012: Vision to Reality, New Delhi, 17–18 October 2005.

Mann, M. and P. Spath. “Life Cycle Assessment of a Biomass Gasification Combined-Cycle Gasification System” (Golden, CO: National Renewable Energy Laboratory, December 1997), pp. 43–44.

Manufacturers of Emissions Controls Association, “Clean Air Facts: Emission Control for Diesel Engines,” (Washington, DC: undated), at www.meca.org/galleries/default-file/dieselfact%200106.pdf.

Marland, G. and A.F. Turhollow. “CO_2 emissions from the production and combustion of fuel ethanol from corn,” *Energy*, vol. 16, no. 11/12, pp. 1307–16.

Martin, J. and A. Faaij. “IEA Bioenergy Task 40: Country Report for the Netherlands” (Paris: International Energy Agency Task 40, Sustainable International Bioenergy Trade, July 2005), p. 23.

Martinot, E. et al. “Renewables 2005: Global Status Report” (Bonn: Renewable Energy Policy Network for the 21st Century, 2005).

Maryland General Assembly, Department of Legislative Services. “Environment - Fast-Fill Compressed Natural Gas Station Program,” Senate Bill 163 (Annapolis: 1 July 2003), at http://mlis.state.md.us/2003rs/fnotes/bil_0003/sb0163.doc.

Mathewson, S.W. “Yeast and Fermentation,” in *The Manual for the Home and Farm Production of Alcohol Fuel* (Berkeley, CA: Ten Speed Press, 1980).

Matthew, E. “Palm Oil is Killing Off the Orang-utan,” Scotsman.com, 24 September 2005.

Matthias, R. “Biomass-to-Liquid Fuels (BtL)—Made by CHOREN. Process, Environmental Impact and Latest Developments,” presentation at the Automobile & Environment at Belgrade EAEC Congress, May 2005.

McAloon, A. et al. “Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks” (Golden, CO: U.S. Department of Agriculture Agricultural Research Service and NREL-Biotechnology Center for Fuels and Chemicals, October 2000).

McCarthy, M. “Wildlife Fear Leaves GM Safety Debate Unresolved,” *The Independent*, 22 July 2003.

McCormick, R.L. “NOx Solutions for Biodiesel” (Golden, CO: NREL and Colorado Institute for Fuels and Engine Research, Colorado School of Mines, February 2003), p. 21.

McCormick, R. “Effects of Biodiesel on NOx Emissions,” presentation to ARB Biodiesel Workgroup, National Renewable Energy Laboratory, Golden, CO, 8 June 2005.

McCormick, R. NREL, Golden, CO, e-mail to Peter Stair, Worldwatch Institute, 20 July 2005.

McKendry, P. “Energy Production from Biomass (Part 3): Gasification Technologies,” *Bioresource Technology*, vol. 83 (2002), pp. 55–63.

McLaughlin, S. B. et al. “High-Value Renewable Energy from Prairie Grasses,” *Environmental Science and Technology,* vol. 36, no. 10 (2002), p. 2124.

McLaughlin, S.B. et al., “Developing Switchgrass as a Bioenergy Crop,” in J. Janick, ed., *Perspectives on New Crops and New Uses* (Alexandria, VA: ASHS Press, 1999), pp. 282–99.

McMillen, S. et al. “Biodiesel: Fuel for Thought, Fuel for Connecticut’s Future” (Storrs, CT: Connecticut Center for Economic Analysis, University of Connecticut, 24 March 2005).

Mead, J. Sales Associate, World Energy Alternatives, conversation with Peter Stair, Worldwatch Institute, 20 August 2005.

MercoPress. “World’s first tallow-biodiesel plant in Brazil,” 27 October 2005.

Miles, T.P.E. et al. “Alkali Deposits Found in Biomass Power Plants: A Preliminary Investigation of Their Extent and Nature” (Golden, CO: National Renewable Energy Laboratory, April 1995).

Miles, T. Sr. “Operating Experience with Ash Deposition in Biomass Combustion Systems,” presentation at Biomass Combustion Conference, Reno, NV, 28–29 January 1992.

Milne, T. et al. “Thermodynamic Data for Biomass Conversion and Waste Incineration” (Golden, CO: Solar Energy Research Institute (now NREL), September 1986).

Minnesota Department of Agriculture. “The Minnesota Ethanol Program,” at www.mda.state.mn.us/ethanol/about.htm#ngcnote, viewed 6 March 2006.

Minten, B, L. Randrianarison, and J.F.M. Swinnen. “Global Retail Chains and Poor Farmers: Evidence from Madagascar,” September 2005, at www.csae.ox.ac.uk/conferences/2006-EOI-RPI/papers/csae/Randrianarison.pdf.

Mobil Oil Australia Pty Ltd. “Mobil Submission to the Australian Government Biofuels Taskforce,” June 2005, at www.pmc.gov.au/biofuels/submissions/submission33.pdf.

Moore, J. et al. “Oil Imports: An Overview and Update of Economic and Security Effects,” CRS Report for Congress 98-1 (Washington, DC: 12 December 1997).

Moreira, J.R. “Global Biomass Energy Potential,” prepared for the Expert Workshop on Greenhouse Gas Emissions and Abrupt Climate Change: Positive Options and Robust Policy (Paris: 2004).

Moreira, J.R. “Global Biomass Energy Potential” (São Paulo: CENIBO, 2004).

Morris, D. Institute for Local Self-Reliance, Minneapolis, MN, “Ownership Matters: Three Steps to Ensure a Biofuels Industry That Truly Benefits Rural America,” presentation at the Minnesota Ag Expo 2006, Morton, MN, 25 January 2006.

Morris, D. “The Ethanol Glass Is Still Only Half Full,” *Ethanol Today*, September 2003.

Mortimer, N.D. et al. “Evaluation of the Comparative Energy, Global Warming and Socio-Economic Costs and Benefits of Biodiesel,” report prepared for the UK Department for Environment, Food and Rural Affairs, Report no. 20/1 (London: January 2003), p. ix.

Mosier, N.C. et al. “Features of promising technologies for pretreatment of lignocellulosic biomass,” *Bioresource Technology*, vol. 96, no. 6 (2005), pp. 673–86.

Mozaffarian, M. and R.W.R. Zwart. “Feasibility of Biomass/Waste-Related SNG Production Technologies,” Novem Project No. 249-01-03-12-0001 (The Hague: Dutch Ministry of Economic Affairs, 2003).

Mudeva, A. “Interview- Malaysia IOI Eyes Green Energy Expansion in Europe,” *Reuters*, 23 November 2005.

Multi-commodity Exchange of India, Ltd. “Castor Oil Profile,” at www.mcxindia.com/castor_oil.aspx, viewed 14 March 2006.

Murray, D. “Ethanol’s Potentail: Looking Beyond Corn,” Eco-Economy Update (Washington, DC: Earth Policy Insitute, 29 June 2005).

Murray, D. “Rising Oil Prices Will Impact Food Supplies,” peopleandplanet.net, 13 September 2005.

Naber, J.E. and F. Goudriaan. “HTU Diesel,” presented at Biofuel BV, Berlin, Germany, November 2003.

Nagarajan, G. et al. “Review of Ethanol in Compression Ignition Engine” (Chennai: Institute for Energy Studies, Anna University), at www.saeindia.org/saeconference/ethanolreview.htm.

Nakicenovic, N. et al. “Global energy perspectives” (Cambridge: International Institute for Applied Systems Analysis/ World Energy Council, 1998).

Nastari, P.M. “Ethanol: The Global Overview,” presentation at International Ethanol Conference, Brisbane, Australia, 9–10 May 2005, at www.sdi.qld.gov.au/dsdweb/v3/documents/objdirctrled/nonsecure/pdf/11584.pdf.

Nastari, P., I. Macedo, and A. Szwarc. “Observations on the Draft Document Entitled ‘Potential for Biofuels for Transport in Developing Countries” report prepared for the World Bank Air Quality Thematic Group (Brazil: 2005).

National Biodiesel Board. “Biodiesel as a Greenhouse Gas Reduction Option” (Jefferson City, MO: 2004), at www.biodiesel.org/resources/reportsdatabase/reports/gen/20040321_gen-332.pdf.

National Biodiesel Board. “Biodiesel Production,” fact sheet (Jefferson City, MO: updated 29 January 2005).

National Biodiesel Board. “Biodiesel Production and Quality Standards,” fact sheet (Jefferson City, MO: updated 11 March 2002).

National Biodiesel Board. “Fuel Fact Sheets: Standards and Warranties,” www.biodiesel.org/resources/fuelfactsheets/standards_and_warranties.shtm, viewed 2 March 2006.

National Biodiesel Board. “Guidance Issued 30 November 2005” (Jefferson City, MO: 30 November 2005), available at www.biodiesel.org/pdf_files/Biodiesel_Blends_Above%20_20_Final.pdf.

National Biodiesel Board. “Study Shows NOx Emissions Reductions in Biodiesel Blends with Additive,” press release (Jefferson City, MO: 4 February 2004).

National Biodiesel Board. “Summary of Recent Studies Citing Economic Attributes Resulting From the Successful Commercialization of Biodiesel in the US,” reports database (Jefferson City, MO: July 1998), at www.biodiesel.org/resources/reportsdatabase/reports/gen/19980701_gen-054.pdf.

National Corn Growers Association. “Taking Ownership of Grain Belt Agriculture,” at www.ncga.com/public_policy/takingOwnership/index.htm, viewed 6 March 2006

National Corn Growers Association. “The World of Corn 2004,” at http://ncga.com/ WorldOfCorn/main.

National Ethanol Vehicle Coalition. “E85 Brochure,” available at www.e85fuel.com.

National Ethanol Vehicle Coalition. “How many E85 compatible vehicles are on American roads today?,” at www.e85fuel.com/e85101/faqs/number_ffvs.php, viewed 10 March 2006.

National Science-Technology Roadshow Trust. “Morton Coutts—Continuous Fermentation System,” at www.roadshow.org/html/resources/scientists/coutts/article.html, viewed 29 January 2006.

Natsource Environmental Services. “Glossary,” available at www.natsource.com/markets/index.asp, viewed January 2006.

Natural Resources Canada. “Government of Canada Launches Ethanol Expansion Program,” press release (Ottawa: 20 October 2003).

Nature Canada. “How Tempting is the Mackenzie Gas Project for Canada’s North?” *Nature Canada*, Summer 2004.

NatureWorks, LLC. Web site, www.natureworksllc.com, viewed 14 November 2005.

Net for Cuba International. “A Brief on the Industrial Sector for Cuba,” www.netforcuba.org/InfoCuba-EN/Economy/ABrief.htm, viewed 12 March 2006.

Netherlands Agency for Energy and Environment (NOVEM). ”Conventional Bio-Transporation Fuels. An Update,” Report 2GAVE-03.10 (Utrecht: May 2003), at www.ecn.nl/_files/bio/Report_2GAVE-03.10.pdf.

New Uses Council, Environmental and Energy Studies Institute, and North Carolina Solar Center. “Development of a Workable Incentives System for Biobased Products, Biofuels and Biopower,” project description, September 2005, p. 3.

Nierenberg, D. *Happier Meals: Rethinking the Global Meat Industry,* Worldwatch Paper 171 (Washington, DC: Worldwatch Institute, 2005).

Noon, C.E. et al. "Transportation and Site Location Analysis for Regional Integrated Biomass Assessment (Riba)," in *Proceeding*s, Bioenergy '96 - The Seventh National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies, Nashville, TN, 15–20 September 1996, at. http://bioenergy.ornl.gov/papers/bioen96/noon1.html.

Novak, N. "The Rise of Ethanol in Rural America," *Ag Decision Maker* (Iowa State University), June 2002.

Novozymes. "Novozymes and NREL reduce enzyme cost," press release (Bagsvaerd, Denmark: 14 April 2005).

Novozymes & BBI International. "Fuel Ethanol: A Technological Evolution" (Grand Forks, ND: June 2005).

Novozymes & BBI International. "Fuel Ethanol Production: Technological and Environmental Improvements, Its History, Its Advancements, Its Future," 26 June 2002.

NTB Liquid Biofuels Network. "NTB Liquid Biofuels Network - The European Network for removing non-technical barriers to the development of liquid biofuels," at www.biomatnet.org/secure/Ec/S1016.htm.

Oak Ridge National Laboratory (ORNL). "Biofuels from Switchgrass: Greener Energy Pastures," brochure (Oak Ridge, TN: undated), at http://bioenergy.ornl.gov/papers/misc/switgrs.html.

ORNL. "Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply" (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy: February 2005), p. 15.

ORNL, "Popular Poplars: Trees for Many Purposes" (Oak Ridge, TN: undated), at http://bioenergy.ornl.gov/misc/poplars.html, viewed 10 March 2006.

Official Journal of the European Union. "Directive 2003/30/EC of the European Parliament and of the Council of 6 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport," 17 May 2005, p. 1.

Ohio Farm Bureau Federation. "Ethanol on the right track at Indy 500," news feature (Columbus. OH: 3 June 2005).

Oil World. "EU Rapeoil Selling Out for Biofuel Use," 19 October 2005.

Olofsson, L. "Swedish government embraces peak oil and looks towards biofuels," *Energy Bulletin*, 17 December 2005.

Olson, D. Director, Trade and Agriculture Project, IATP, e-mail to L. Sorkin, Worldwatch Institute, 27 February 2006.

Ontario Ministry of Agriculture, Food and Rural Affairs. "McGuinty Government Takes Next Steps on Cleaner Air," press release (Toronto, ON: 7 October 2005).

Organic Consumers Association. "How Great is the Impact of GMOs on Organic?" (Finland, MN: June 2005).

Organisation for Economic Co-operation and Development. "Agricultural Market Impacts of Future Growth in the Production of Biofuels" (Paris: Working Party on Agricultural Policies and Markets, 2006).

Oxfam International. "The EU Sugar Scam: How Europe's sugar regime is devastating livelihoods in the developing world," Oxfam Briefing Paper 27 (Oxford, UK: 2002).

Pacca, S. University of São Paulo, reviewer comments, 13 February 2006.

Panoutsou, C. Center for Renewable Energy Sources, “Agricultural & Forestry Biomass in EU-25,” presented at the 1st International Biorefinery Workshop (Washington, DC: 20–21 July 2005).

Park, S. et al. “Identifying On-farm Management Practices Aimed at Reducing Greenhouse Gas Emissions from Sugarcane Primary Production,” in *Proceedings of the 11th Australian Agronomy Conference, 2–6 February 2003* (Geelong, Victoria: Australian Society of Agronomy, 2004).

Pascual, L.M. and R.R. Tan. “Comparative Life Cycle Assessment of Coconut Biodiesel and Conventional Diesel for Philippine Automotive Transportation and Industrial Boiler Application” (Manila: College of Engineering, De La Salle University), p. 6, available at www.lcacenter.org/InLCA2004/papers/Pascual_L_paper.pdf.

Paster, M., J. Pellegrino, and T. Carole. “Industrial Bioproducts: Today and Tomorrow,” prepared by Energetics, Inc., for the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, Office of the Biomass Program (Washington, DC: July 2003).

Pataki, Governor G. “State of the State Address,” 4 January 2006, at www.ny.gov/governor/2006_sos/sosaddress_text.html.

Patzek, T. “Thermodynamics of the Corn-Ethanol Biofuel Cycle,” *Critical Reviews in Plant Sciences*, vol. 23, no. 519 (2004).

Pearce, F. “Forests paying the price for biofuels,” *New Scientist*, 22 November 2005.

Pedersen, J.R., A. Ingemarsson, and J.O. Olsson, “Oxidation of Rapeseed Oil, Rapeseed Methyl Ester (RME) and Diesel Fuel Studied with GC/MS,” *Chemosphere*, vol. 38, no. 11 (1999), pp. 2467–74, cited in Jürgen Krahl et al., “Comparison of biodiesel with different diesel fuels regarding exhaust gas emissions and health effects,” 2001, at www.ufop.de/downloads/Biodiesel_comparison.pdf.

Peng, S. et al., “Rice yields decline with higher night temperature from global warming,” *Proceedings of the National Academy of Sciences*, 6 July 2004, pp. 9971–75.

Pennsylvania Department of Environmental Protection. “Automobile Emissions: An Overview,” at www.dep.state.pa.us/dep/subject/pubs/arr/aq/fs1829.pdf, viewed June 2005.

Peplow, M. “Ethanol Production Harms Environment, Researchers Claim,” *Nature*, 1 July 2005.

Perlack, R.D. et al. “Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion Ton Annual Supply” (Oak Ridge, TN: ORNL, April 2005).

Perlack, R.D. et al. “Biomass Fuel from Woody Crops for Electric Power Generation” (Oak Ridge, TN: ORNL, 21 September 1995), at http://bioenergy.ornl.gov/reports/fuelwood/toc.html.

Pew Initiative on Food and Biotechnology. “Have Transgenes—Will Travel: Issues Raised by the Gene Flow from Genetically Engineered Crops” (Washington, DC, August 2003).

Philippine Fuel Ethanol Alliance. “Bioethanol Benefits: Energy, Environment, Employment” (Makati City: 2005), at www.bioethanol.com.ph/bioethanol/benefits.html, viewed 7 March 2006.

Pia Palermo, M. “Brazil Losing Fight to Save the Amazon,” *Reuters*, 23 May 2005.

Pimentel, D. “Ethanol Fuels: Energy Balance, Economics and Environmental Impacts are Negative,” *Natural Resources Research*, vol. 12, no. 2 (2003), pp. 127–134.

Pimentel, D. and J. Krummel. "Biomass Energy and Soil Erosion: Assessment and Resource Costs," *Biomass*, vol. 14 (1987), pp. 15–38.

Pimentel, D. and T. Patzek. "Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower," *Natural Resources Research*, vol. 14, no. 1 (2005), p. 65.

Pollan, M. "When a Crop Becomes King," *New York Times*, 19 July 2002.

Postel, S. "Safeguarding Freshwater Ecosystems," in Worldwatch Institute, *State of the World 2006* (New York: W.W. Norton & Company, 2006), p. 52.

Powlson, D.S., A.B. Riche, and I. Shield. "Biofuels and Other Approaches for Decreasing Fossil Fuel Emissions from Agriculture," *Annals of Applied Biology*, vol. 146 (2005), pp. 193–201.

PR Newswire. "ADM Plans to Expand Ethanol Capacity by 500 Million Gallons," 4 October 2005.

Prado, L. Director of Brazil Programs, LaGuardia Foundation, e-mail to S. Hunt, Worldwatch Institute, 28 January 2006.

Public Citizen. "Down on the Farm: NAFTA's Seven-Years War on Farmers and Ranchers in the U.S., Canada and Mexico" (Washington, DC: 2001).

Quirin, M. et al. "CO2 Mitigation through Biofuels in the Transport Sector: Status and Perspectives, Main Report" (Heidelberg: Institute for Energy and Environmental Research, August 2004).

Radich, A. "Biodiesel Performance, Costs, and Use" (Washington, DC: DOE, Energy Information Agency (EIA), updated 8 June 2004, at www.eia.doe.gov/oiaf/analysispaper/biodiesel.

Rainforest Alliance. "Standard for Sustainable Agriculture — Sustainable Agriculture Network," at www.rainforest-alliance.org/programs/agriculture/certified-crops/standards.html.

Rainforest Alliance. "Sustainable Agriculture Network," at www.rainforest-alliance.org/programs/agriculture/san/index.html.

Ramesohl, S. and K. Arnold. "Analyse und Bewertung der Nutzungsmöglichkeiten von Biomasse - Band 1: Gesamtergebnisse und Schlussfolgerungen," study prepared for Bundesverband Gas- und Wasserfach and Deutsche Vereinigung des Gas- und Wasserfachs (Wuppertal: Wuppertal Institute for Climate, Energy, Environment, November 2005).

Randewich, N. "Central American Poor Struggle as Oil Prices Rise," *Reuters*, 14 September 2005.

Ranney, J.W. and L.K. Mann. "Environmental Considerations in Energy Crop Production," *Biomass and Bioenergy*, vol. 6 (1994), pp. 211–228, cited in T.H. Green et al., "Environmental Impacts of Conversion of Cropland to Biomass Production," *Proceedings*, BIOENERGY '96 - The Seventh National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies, September 15–20, 1996, Nashville, TN, available at bioenergy.ornl.gov/papers/bioen96/green.html.

Ray, D.E., D.G. De La Torre Ugarte, and K.J. Tiller. "Rethinking US Agricultural Policy: Changing Course to Secure Farmer Livelihoods Worldwide" (Nashville: Agricultural Policy Analysis Center The University of Tennessee, 2003).

Regmi, A. et al. "Changing Structure of Global Food Consumption and Trade" (Washington, DC: USDA Economic Research Service, 2001).

Remmele, E. “Position Paper: Technologie-und Forderzentrum im Kimpetenzzentrum fur Nachwachsende Rohstoffe,” 2004, p. 5.

Renewable Fuels Association (RFA). “Ethanol Facts: Economy” and “Ethanol Trade Fact Sheet,” fact sheets (Washington, DC: 2005), at www.ethanolrfa.org/resource/facts.

RFA. “Federal Regulations: VEETC,” at www.ethanolrfa.org/policy/regulations/federal/veetc.

RFA. “Homegrown for the Homeland: Ethanol Industry Outlook 2005” (Washington, DC: 2005), at www.ethanolrfa.org/objects/pdf/outlook/outlook_2005.pdf.

RFA. “Industry Statistics,” at www.ethanolrfa.org/industry/statistics/#A, viewed 10 March 2006.

RFA. “Plant Locations,” at www.ethanolrfa.org/industry/locations, viewed 3 April 2006.

RFA. “U.S. Ethanol Industry Surpasses First Year Goal of RFS,” press release (Washington, DC: 25 November 2005).

RenewableEnergyAccess.com. “Biodiesel Mandate for Navy and Marine Facilities,” 22 March 2005.

RenewableEnergyAccess.com. “DynaMotive to Make BioOil in Ukraine and Baltic States,” 31 January 2006.

RenewableEnergyAccess.com. “New York Announces New Energy Plans,” 19 September 2005.

RenewableEnergyAccess.com. “State Legislation Focuses on Tax Incentives for Wind, Biofuels,” 28 April 2005.

Renner, M. *The Anatomy of Resource Wars*, Worldwatch Paper 162 (Washington, DC: Worldwatch Institute, 2002).

Renner, M. “Oil Spills Decline,” in Worldwatch Institute, *Vital Signs 2002* (New York: W.W. Norton & Company, 2002).

Reuters. “China to Put Corn Into Gas Tanks to Clean Up,” 20 October 2003.

Reuters. “Ethanol Starting to Trade Like a World Commodity,” 29 September 2005.

Reuters. “Germany Sets Quotas for Biofuel in Fuel from 2007,” 3 May 2006.

Reuters. “Grape Biofuel May Lift the Spirits of French Vinters,” 16 November 2005.

Reuters. “Interview: Farmers Are ‘Tomorrow’s Sheiks” Due to Biofuels,” 10 November 2005.

Reuters. “Kemira to Invest in New Technology,” 6 September 1999.

Reuters. “Most in US Would Shun Labeled Biotech Foods – Poll,” 16 July 2003.

Reuters. “Thais to Invest $20 Billion in Energy Sector in 4 Years,” 17 May 2005.

Reuters. “Zimbabwe Says to Reopen Ethanol Fuel Plant,” 19 July 2005.

Richards, I.R. “Energy balances in the growth of oilseed rape for biodiesel and of wheat for bioethanol,” report prepared for the British Association for Bio Fuels and Oils (BABFO) (Levington Park Ipswich, Suffolk, UK: Levington Agriculture Ltd., June 2000), at www.biodiesel.co.uk/levington.htm.

Riesing, T.F. “Cultivating Algae for Liquid Fuel Production,” *The Permaculture Activist*, March 2006, pp. 48–50.

Rockefeller Foundation and Scientific & Industrial Research & Development Centre. “The Potential of *Jatropha curcas* in Rural Development and Environment Protection – An Exploration,” concept paper for a workshop sponsored by the Rockefeller Foundation and Scientific & Industrial Research & Development Centre, Harare, Zimbabwe,13–15 May 1998, available at www.jatropha.de/zimbabwe/rf-conf1.htm.

Rodrigues, R.A. “Biodiesel in Brazil—An Overview,” PowerPoint presentation at the III German-Brazilian Workshop on Biodiesel, Fortaleza-Ceara, Brazil, 1 July 2005, at www.ahk.org.br/inwent/palestras/rodrigo_rodrigues.ppt.

Rohter, L. “A Record Amazon Drought, and Fear of Wider Ills,” *New York Times*, 11 December 2005.

Romanowicz, G. “UK and Europe push for ‘right kind’ of biofuels,” edie.net, 3 March 2006.

Rosillo-Calle, F. “Biomass (Other Than Wood),” in World Energy Council, *Survey of Energy Resources 2001* (London: 2001).

Roundtable on Sustainable Palm Oil (RSPO). “RSPO Adopts the Principles and Criteria for Sustainable Palm Oil Production,” press release (Singapore: 23 November 2005).

RSPO. “Frequently Asked Questions,” at www.sustainable-palmoil.org/FAQs.htm.

RSPO. “RSPO Principles and Criteria for Sustainable Palm Oil Production,” public release version (Kuala Lumpur: 17 October 2005).

RSPO, “Sustainable Palm Oil Production Principles set out 15 December 2005,” at www.sustainable-palmoil.org, viewed 7 March 2006.

RSPO. “The Malaysian Palm Oil Association (MPOA)” (Singapore: 2005), at www.sustainable-palmoil.org/profile.htm.

Rubin, J. and P. Buchanan. “The Global Crude Supply Outlook: Tighter Markets Ahead,” *CIBC World Markets Inc, Monthly Indicators*, 9 January 2006.

Rubin, J. “The Time of Sands,” *CIBC World Markets Inc, Monthly Indicators*, 9 January 2006.

RWE Aktiengesellschaft. “World Energy Report 2005: Determinants of Energy Prices” (Essen: 2005), p. 36.

Saint, W.S. “Farming for Energy: Social Options under Brazil’s National Alcohol Programme.” World Development, vol. 10, no. 3 (1982), pp. 223–38.

Sakamoto Yakuhin Kogyo, Ltd. “Glyerol,” at www.sy-kogyo.co.jp/English/sei/1_gly.html, viewed 22 May 2005.

Salazar, K. “Report on the 2006 Colorado Renewable Energy Summit” (Denver: 16 Februrary 2006), at http://salazar.senate.gov/images/pdf/SummitReport060216.pdf.

Salchenegger, S. and W. Pölz, “Biogas im Verkehrssektor – Technische Möglichkeiten, Potenziale und Umweltrelevanz” (Vienna: Umweltbundesamt, 2005).

Sample, D.W., L. Paine, and A. Roth. "Harvested Switchgrass Fields Provide Habitat for Declining Grassland Birds," paper presented at BioEnergy '98: Expanding Bioenergy Partnerships, Madison, WI, 4–8 October 1998.

Sanchez, S. et al. "The fermentation of mixtures of D-glucose and D-xylose by Candida shehatae, Pichia stipitis or Pachysolen tannophilus to produce ethanol," *Journal of Chemical Technology and Biotechnology*, vol. 77, no. 6 (2002), pp. 641–48.

Santos, O.J.F. "Environmental Aspects of Miscanthus Production," in M.B. Jones and M. Walsh, eds., *Miscanthus for Energy and Fibre* (London, James and James: 2001), pp. 46–47, cited in D.S. Powlson, A.B. Riche, and I. Shield, "Biofuels and Other Approaches for Decreasing Fossil Fuel Emissions from Agriculture," *Annals of Applied Biology*, vol. 146 (2005), pp. 193–201.

São Paulo State Environment Agency (CETESB). Relatório de Qualidade do Ar no Estado de São Paulo, 2003.

Sasol. "Explore Sasol: Sasol in Fuels" (Johannesburg: 12 August 2004), at www.sasol.com/sasol_internet/frontend/navigation.jsp?navid=600003&rootid=2, viewed 7 March 2006.

Scania Brasil. personal communication with A. Szwarc, Director, ADS Tecnologia e Desenvolvimento Sustentável, São Paulo, Brazil, 2001.

Scharmer, K. and G. Gosse. "Energy balance, ecological impact and economics of vegetable oil methylester production in Europe as a substitute for fossil diesel," report commissioned by GET Germany and INRA France (Brussels: EU ALTENER Programme, 1996).

Scheffer, K. and M. Karpenstein-Machan. *Ökologischer und Ökonomischer Wert der Biodiversität am Beispiel der Nutzung von Energiepflanzen,* Schriftenreihe der Zentralstelle für Agrardokumentation und –information, Informationszentrum Genetische Ressourcen (IGR), Band 16 (Witzenhausen: 2001), pp. 177–192;

Schiller, A. and V.R. Tolbert. "Hardwood Energy Crops and Wildlife Diversity: Investigating Potential Benefits for Breeding Birds and Small Mammals" (Oak Ridge, TN: Oak Ridge Associated Universities and Biofuels Feedstock Development Program, Oak Ridge National Laboratory (ORNL), 1996), available at http://bioenergy.ornl.gov/papers/bioen96/schiler1.html.

Schlamadinger, B. and G. Marland. "Some Results from the Graz/Oak Ridge Carbon Accounting Model (GORCAM).

Schmitz, N., ed. *Bioethanol in Deutschland* (Münster: Schriftenreihe Nachwachsende Rohstoffe, Band 21, 2003), p. 25.

Schmitz, N. et al., eds. *Innovationen bei der Bioethanolerzeugung. Schriftenreihe, Nachwachscende Rohstoffe. Band 26*. (Bonn: German Federal Ministry of Food, Agriculture and Consumer Protection and Germany Agency of Renewable Resources, 2005).

Schneider, R. et al. *Sustainable Amazon: Limitations and Opportunities for Rural Development* (Washington, DC: World Bank & Imazon, Brazil: 2000), cited in A. Casson, "Oil Palm, Soybeans & Critical Habitat Loss," review prepared for the WWF Forest Conversion Initiative (Zurich: August 2003), p. 17.

Schope, M. and G. Britschkat. "Macroeconomic Evaluation of rape cultivation for biodiesel production in Germany" (Munich: Institut fur Wirtschaftsforschung, March 2002).

Science Daily. "Hybrid Grass May Prove to be Valuable Fuel Source," 9 September 2005.

Scurlock, J. “Bioenergy Feedstock Characteristics” (Oak Ridge, TN: ORNL, 2000).

Sen, A. “Why Half the Planet Is Hungry,” *Observer of London*, 16 June 2002.

Sethi, K.S. “Biofuels 2012: Vision to Reality,” Planning Commission, 2003, www.teriin.org/events/docs/5biofuel.htm, viewed 18 October 2005.

Severinghaus, J. “Why we import Brazilian ethanol,” trade report (West Des Moines, IA: Iowa Farm Bureau Federation, 14 July 2005).

Seyfried, F. “RENEW – Renewable Fuels for Advanced Powertrains,” 1st Year Report for EU 6th Framework Integrated Project, 2005, available at www.renew-fuel.com.

Shapouri, H. Senior Economist, USDA, conversation with P. Stair, Worldwatch Institute, 15 December 2005.

Shapouri, H. Senior Economist, USDA, e-mail to P. Stair, Worldwatch Institute, 10 January 2006.

Shapouri, H. “The 2001 Net Energy Balance of Corn-Ethanol” (Washington, DC: USDA, 2004).

Shapouri, H. et al. “Energy Balance/Life Cycle Inventory for Ethanol, Biodiesel and Petroleum Fuels” (Washington, DC: U.S. Department of Agriculture (USDA), July 2005).

Shapouri, H., J.A. Duffield, and M. Wang, “The Energy Balance of Corn Ethanol: An Update,” Agricultural Economic Report No. 813 (Washington, DC: USDA Office of Energy Policies and New Uses, 2002).

Sharp, C.A. “Exhaust Emissions and Performance of Diesel Engines with Biodiesel Fuels” (San Antonio, TX: Southwest Research Institute, July 1998).

Sheehan, J. et al. “A Look Back at the U.S. Department of Energy’s Aquatic Species Program: Biodiesel from Algae” (Golden, CO: NREL, 1998).

Sheehan, J. et al. “An Overview of Biodiesel and Petroleum Diesel Life Cycles” (Golden, CO: NREL, May 1998).

Sheehan, J. et al. “Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol,” *Journal of Industrial Ecology*, vol. 7, no. 3–4 (2004).

Sheehan, J. et al. “Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in An Urban Bus” (Golden, CO: National Renewable Energy Laboratory, May 1998).

Shell International, “The evolution of the world's energy system 1860-2060” (London: Shell Center, 1995).

Sherertz, P.C. “Petroleum Products” (Richmond, VA: Virginia Department of Health, 30 June 1998), at www.vdh.state.va.us/HHControl/petrofac.PDF.

Sierra Club of Canada. “Mackenzie Pipeline to Fuel America’s Gas Tank,” press release (Ottawa: 14 April 2004).

Simon, S. “To replace oil, U.S. experts see amber waves of plastic,” *Los Angeles Times*, 28 June 2005.

Singh, R. “Literature Review on Biodiesel,” The University of the South Pacific, written for The South Pacific Applied Geoscience Commission (Suva, Fiji: undated).

Singh, V. et al. “Modified Dry Grind Ethanol Process” (Champaign, IL: University of Illinois at Urbana-Champaign Agricultural Engineering Department, 18 July 2001).

Sinico, S. “Fill it Up with Natural,” dw-world.de, 22 September 2005, at hwww.dw-world.de/dw/article/0,2144,1717299,00.html.

Sino-German Workshop on Energetic Utilization of Biomass. Beijing, 8–11 October 2003, at www.ipe.ac.cn/sinogerman/program.htm.

Smeets, E., A. Faaij, and I. Lewandowski. “A quickscan of global bioenergy potentials to 2050” (Utrecht: Copernicus Institute, Utrecht University: March 2004).). Updated results obtained from the authors, March 2006.

Smeets, E., A. Faaij, and I. Lewandowski. “The impact of sustainability criteria on the costs and potentials of bioenergy production,” (Utrecht: Copernicus Institute, Utrecht University, May 2005).

Smil, V. “Eating meat: evolution, patterns, and consequences,” *The Population and Development Review*, vol. 28, no. 4 (2002), pp. 588–639.

Society of Petroleum Engineers (SPE). “How is the Industry Working to Protect the Environment?”, at www.spe.org/spe/jsp/basic/0,,1104_1008218_1109940,00.html, viewed June 2005.

SPE. “Seismic Technology,” at www.spe.org/spe/jsp/basic/0,,1104_1714_1004089,00.html, viewed June 2005.

Somera, B. J. and K.K. Wu. “Energy Inventory of Hawaiian Sugar Plantations—1995,” Energy Report 35 (Alea, HI: Hawaii Agriculture Research Center, August 1996).

Sorensen, B. “Long-term scenarios for global energy demand and supply: Four global greenhouse mitigation scenarios” (Roskilde: Roskilde University, Insitute 2, Energy & Environment Group, 1999).

Staiss, F. *Jahrbuch Erneuerbare Energien* (Stuttgart: 2003), p. 11.

Stat Communications. “Biodiesel lifts German rapeseed area,” statpub.com, 21 February 2006, at www.statpub.com/open/183421.phtm.

Strossman, C. “European Union Sugar Annual 2004,” *GAIN Report* (Washington, DC: USDA, FAS, 8 April 2004.

Sun Star Magazine. “Biodiesel plant seen to help coco industry,” 9 June 2005.

Sustainable International Bioenergy Trade. Web site, www.bioenergytrade.org.

Sutton, M.C., N. Klein, and G. Taylor. “A Comparative Analysis of Soybean Production Between the United States, Brazil, and Argentina,” *Journal of the American Society of Farm Managers and Appraises,* 2005, at www.asfmra.org/documents/Sutton33_41.pdf.

Swisher, J. and D. Wilson. “Renewable energy potentials,” *Energy,* vol. 18, no. 5 (1993), pp. 437–59.

Szwarc, A. Director, ADS Tecnologia e Desenvolvimento Sustentável, São Paulo, Brazil, personal communication with Worldwatch Institute, 2006.

Talks, P. “EU-25 Grain and Feed Semi-Annual 2004,” *GAIN Report* (Washington, DC: USDA, Foreign Agricultural Service, 8 December 2004).

Tampier, M. et al. "Identifying Environmentally Preferable Uses for Biomass Resources, Stage 2 Report: Life-Cycle GHG Emissions Reduction Benefits of Selected Feedstock-to-Product Threads," prepared for Natural Resources Canada and National Research Council Canada (North Vancouver, BC: Envirochem Services Inc., 19 July 2004).

Tanzania Traditional Energy Development and Environment Organisation (TaTEDO). "Biofuels for Transportation in Tanzania Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Dar es Salaam: September 2005).

Television Trust for the Environment. "Power Pods—India," Hands On-Ideas to Go, Series 4 (London: February 2004), at www.tve.org/ho/doc.cfm?aid=1433.

Termath, S. "Biodiesel und Biodieselbeimischung-Kraftstoffqualitaten als Voraussetzung fur den Marktzugang und erste Emissionsmessung," presentation at the Fuels for the Future Congress (Essen: March 2005).

The Bangkok Post. "Thailand looking to import ethanol to mix with petrol," 5 September 2005.

The Economist. "Recycling the Petrodollars," 12 November 2005.

The Economist. "Living and Dying on History and Artificial Economic Sweeteners," 24 September 2005.

The Energy and Resources Institute (TERI). "Liquid Biofuels for Transportation: India Country Study on Potential and Implications for Sustainable Agriculture and Energy," report prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (New Delhi: October 2005).

TERI. "Seminar on trade liberalization in Environmental Goods and Services" (New Delhi: 16 May 2003).

"The Gleneagles Communiqué." (Gleneagles, Scotland: 6-8 July 2005), at www.fco.gov.uk/Files/kfile/PostG8_Gleneagles_Communique.pdf;

The Manila Times. "Ethanol bill to become law before year-end," 15 October 2005.

The Mariner Group. "History," at www.marinergroup.com/oil-spill-history.htm.

The Miami Herald. "Tons of Sugar, But Biofuels Controversy Remains," 1 August 2005.

The New Rules Project. "Ethanol Production—The Minnesota Model," at www.newrules.org/agri/ethanol.html, viewed 3 April 2006.

The New York Board of Trade. Web site, www.nybot.com.

Thompson, S. "Biodiesel with attitude: Colorado's Blue Sun Biodiesel grows rapeseed for biodiesel production," *Rural Cooperatives* (USDA), November/December 2004.

Thrän, D. et al. "Nachhaltige Biomassenutzungsstrategien im europäischen Kontext: Analyse im Spannungsfeld nationaler Vorgaben und der Konkurrenz zwischen festen, flüssigen und gasförmigen Bioenergieträgern," final report for the German Federal Ministry for the Environment (Leipzig/Hamburg/Hohenheim/Darmstadt: 2006), at www.ie-leipzig.de/Biomassenutzung/Biomasse.htm,

Togola, I. Mali Folkecenter, Bamako, Mali, visit to Worldwatch Institute, Washington, DC, 26 July 2005.

Total Corporation. "Alternative Energies, Promising New Technologies," at www.total.com/en/group/corporate_social_responsibility/future_energy/energy_supply/alternative_energies_6676.htm, viewed 10 March 2006.

Towler, G.P. et al. "Development of a Sustainable Liquid Fuels Infrastructure Based on Biomass" (Des Plaines, Illinois: UOP Innovation Group, 2003).

Transpetro. "Condições Gerais de Serviço – Álcool" (Rio de Janeiro: November 2005), at www.transpetro.com.br/portugues/negocios/dutosTerminais/files/CGSA.pdf.

Trechow, P. "NRW plant Modellversuch mit Ehtanolkraftstoff E-85," *VDI Nachrichten*, no. 25 (2005).

Tretter, H. "Development of Biodiesel in Austria," PowerPoint presentation, Austrian Energy Agency (Vienna: 28 February 2005).

Trettin, C., A. Davis, and J. Parsons. "Sustainability of High-Intensity Forest Management with Respect to Water and Soil Quality and Site Nutrient Reserves," prepared by U.S. Forest Service, Southern Research Station and North Carolina State University (Oak Ridge, TN: U.S. Department of Energy (DOE), Office of Biomass, Oak Ridge National Laboratory, August 2003).

Trindade, S.C."Beyond petroleum and towards a biomass-based sustainable energy future: opportunities for financing sustainable development and carbon trade," *Renewable Energy Partnerships for Poverty Eradication and Sustainable Development* (Partners for Africa), May 2005, p. 6.

Trindade, S.C. President, SE2T International, Ltd., January 2006.

Trindade, S.C. "Transfer of clean(er) technologies to developing countries," in R.U. Ayres and U.E. Simonis, eds., *Industrial Metabolism: Restructuring for Sustainable Development* (New York: United Nations University Press, 1994), pp. 319–36.

Turley, D. Scientist and co-author of a study commissioned by the Home Grown Cereals Authority in the UK and completed early 2005, cited in "UK Study Sees Biofuel Yielding Mixed Green Impact," *Reuters*, 17 May 2005.

Uniao da Agroindustria Canavieira do Estado de São Paulo (UNICA). "Brasil Agroindustria da Cana de Acucar" (São Paulo: 2005).

United Auto Workers. "The American Auto Industry in Crisis: The threat to middle-class jobs, wages, health care, and pensions," *United Auto Workers News and Views,* 8 December 2005.

United Kingdom Department for Transportation. "Towards a UK Strategy for Biofuels—Public Consultation," (London, 26 April 2004), at www.dft.gov.uk/stellent/groups/dft_roads/documents/page/dft_roads_028393.hcsp.

United Kingdom Onshore Pipeline Operators' Association. "Worldwide Pipeline Incidents–April 2002," at www.ukopa.co.uk/publications/pdf/020035.pdf, viewed 5 March 2006.

United States Department of Agriculture (USDA), Economic Research Service. "Rural population and migration: rural population change and net migration," at www.ers.usda.gov/briefing/population/popchange, viewed 6 March 2006.

USDA, Farm Service Agency. "FY 2005 Production of Bioenergy Program Participants and Payments Earned by Commodity" (Kansas City, MO: 12 December 2005), at www.fsa.usda.gov/daco/bioenergy/2005/FY2005ProductPayments.pdf.

USDA, Foreign Agricultural Service. “Counselor and Attache Reports Official Statistics, Estimates for March 2004/2005” (Washington, DC: Cotton, Oilseeds, Tobacco and Seeds Division, March 2006), at www.fas.usda.gov/oilseeds/circular/2006/06-03/table1t3.pdf.

USDA, Foreign Agricultural Service. “Oilseeds: World Markets and Trade,” Circular Series FOP106 (Washington, DC: January 2006).

USDA, Foreign Agricultural Service. “Production, Supply & Distribution database,” at www.fas.usda.gov/psd/complete_files/HTP-0612000.csv.

USDA. *Grain Transportation Report* (Washington, DC: 15 December 2005).

USDA, Soil Quality Institute. “Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations,” (Washington, DC: 4 March 2003), pp. 2–6.

USDA, Transportation and Marketing Programs/Transportation Services Branch. *Grain Transportation Report* (Washington, DC: 22 December 2005).

U.S. Department of Energy (US DOE). “Biodiesel Blends Fact Sheet” (Washington, DC: April 2005).

US DOE. “Black Liquor Gasification Expected to Yield Energy, Environmental, and Environmental Benefits” (Washington, DC: Fall 2001), at www1.eere.energy.gov/industry/bestpractices/fall2001_black_liquor.html.

US DOE. “Dilute Acid Hydrolysis” at www.eere.doe.gov/biomass/dilute_acid.html, viewed 16 May 2005.

US DOE. “DOE Announces $160 million for biorefinery contruction,” press release (Washington, DC: 22 February 2006).

US DOE. “Roadmap for Agriculture Biomass Feedstock Supply in the United States” (Washington, DC: November 2003).

US DOE, Energy Information Administration (EIA). *Annual Energy Outlook 2005* (Washington, DC: February 2005).

US DOE, EIA. *Annual Energy Outlook 2006* (Washington, DC: February 2006)**.**

US DOE, EIA. *Annual Energy Review 2001* (Washington, DC: 2002).

US DOE, EIA. “International Petroleum (Oil) Prices and Crude Oil Import Costs,” at www.eia.doe.gov/emeu/international/oilprice.html, viewed February 2006.

US DOE, EIA. *International Energy Annual 2002* (Washington, DC: 2004).

US DOE, EIA. *Petroleum Information Monthly* (Washington, DC: February 2006).

US DOE, EIA. *Petroleum Supply Annual 2004, Volume 1* (Washington, DC: 2005).

US DOE, EIA. *Short Term Energy Outlook* (Washington, DC: 7 February 2006).

US DOE, EIA. “West Texas Intermediate Crude Oil Price,” *Short-Term Energy Outlook* (Washington, DC, 2006), www.eia.doe.gov/emeu/steo/pub/gifs/Slide2.gif.

US DOE, Federal Energy Management Program. “Biomass and Alternative Methane Fuel Super ESPCs Helping Federal Facilities Turn Waste into Energy,” *FEMP Focus*, November 2002

US DOE, National Energy Technology Laboratory. “Current Industry Perspective: Gasification, World Survey Results 2004” (Pittsburgh, PA: 2005), at www.netl.doe.gov/publications/brochures/pdfs/Gasification_Brochure.pdf.

US DOE, Office of Energy Efficiency and Renewable Energy (EERE). “Biofuels and the Economy,” at http://permanent.access.gpo.gov/websites/www.ott.doe.gov/biofuels/economics.html

US DOE, EERE, “Net Energy Balance for Bioethanol Production and Use,” at www1.eere.energy.gov/biomass/net_energy_balance.html, updated 8 February 2006.

US DOE, EERE. “Novozymes and NREL cut cost of converting biomass to ethanol,” *EERE Network News*, 20 April 2005.

US DOE, EERE, “Pretreatment Technology Evaluation”, at www1.eere.energy.gov/biomass/technology_evaluation.html , viewed 16 May 2005.

US DOE, EERE. “Pyrolysis and Other Thermal Processing” (Washington, DC: 2005), at www1.eere.energy.gov/biomass/pyrolysis.html.

US DOE, EERE. “Roadmap for Agricultural Biomass Feedstock Supply in the United States” (Washington, DC: November 2003).

United States Environmental Protection Agency (US EPA). “A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions, Draft Technical Report,” (Washington, DC: October 2002).

US EPA. “EPA Upholds Reformulated Gas Requirement in California, New York, and Connecticut,” press release (Washington, DC: 2 June 2005).

US EPA. “Health and Environmental Impacts of NOx,” at www.epa.gov/air/urbanair/nox/hlth.html..

United States General Accounting Office. “Petroleum and Ethanol Fuels: Tax Incentives and Related GAO Work,” Letter to Senator Tom Harkin, 25 September 2000, at www.gao.gov/new.items/rc00301r.pdf.

United States Geological Survey. “Subsidence and Fault Activation Related to Fluid Energy Production, Gulf Coast Basin Project” (Washington, DC: Coastal and Marine Geology Program 21 March 2005), at http://coastal.er.usgs.gov/gc-subsidence/overview.html.

United States National Aeronautics and Space Administration. “2005 Warmest Year in Over a Century,” news feature (Washington DC: 24 January 2006), at www.nasa.gov/vision/earth/environment/2005_warmest.html.

United States National Renewable Energy Laboratory (NREL). “Biomass for Sustainable Transportation” (Golden, CO: 2000), at www.nrel.gov/docs/fy00osti/25876.pdf.

NREL. “Hannepin County’s Experience with Heavy-Duty Ethanol Vehicles” (Golden, CO: January 1998).

NREL. Mustard Seed Research Program presentation (Golden, CO: March 2002), at www.nrel.gov/docs/gen/fy02/31794.pdf.

NREL. “The Biomass Economy,” National Renewable Energy Laboratory 2002 Research Review, July 2002.

NREL. “Thermochemical Conversion Technologies-Projects,” at www.nrel.gov/biomass/proj_thermochemical_conversion.html, viewed 16 May 2005.

United States Senate. “U.S. Renewable Fuels Standard,” in *Energy Policy Act of 2005*, pp. 141–172, at http://energy.senate.gov/public/_files/H6_EAS.pdf.

United Nations. *Energy Statistics Yearbook* (New York: 1997).

United Nations Conference on Trade and Development, “UNCTAD Launches the Biofuels Initiative,” press release (Geneva: 21 June 2005).

United Nations Environment Programme (UNEP). *Global Environment Outlook, GEO-2000* (Nairobi 2000).

UNEP. Sustainable Energy Finance Initiative Web site, www.sefi.unep.org.

United Nations Food and Agriculture Organization (FAO). “Agriculture, Trade and Poverty: Can Trade Work for the Poor,” in *The State of Food and Agriculture* (Rome: 2005).

FAO (2002). Cited in Leonard Gianessi, Sujatha Sankula, and Nathan Reigner, “Plant Biotechnology: Potential Impact for Improving Pest Management in European Agriculture: Herbicide Tolerant Wheat Case Study” (Washington, DC: National Center for Food & Agricultural Policy, December 2003).

FAO. FAOSTAT electronic database, at http://faostat.fao.org.

FAO. “Proceedings of the Validation Forum on the Global Cassava Development Strategy,” Rome, 26–28 April, 2000, at www.fao.org/documents/show_cdr.asp?url_file=/docrep/007/y2413e/y2413e07.htm.

FAO, Statistics Division. “Major Food and Agricultural Commodities and Producers,” at www.fao.org/es/ess/top/commodity.jsp?commodity=270&lang=EN&year=2004.

FAO and International Institute for Applied Systems Analysis (IIASA). *Global Agro-Ecological Zones (Global-AEZ)*, CD-ROM (Rome and Laxenburg, Austria: 2000), at www.fao.org/landandwater/agll/gaez/index.htm.

United Nations Framework Convention on Climate Change, “Key GHG data—GHG Emission Data for 1990-2003” (Bonn: 2005), p. 69, cited in EC, “Commission Staff Working Document, Annex to the Communication from the Commission: An EU Strategy for Biofuels, Impact Assessment” (Brussels: 2006), p. 4.

University of California Agriculture and Natural Resources. “Reduce Pollution With Proper Fertilizer Timing,” at http://ucanr.org/delivers/impactview.cfm?impactnum=249&mainunitnum=0, viewed June 2005.

Urbanchuk, J.M. “The Contribution of the Ethanol Industry to the American Economy in 2004” (Wayne, PA: 12 March 2004), at www.ncga.com/ethanol/pdfs/EthanolEconomicContributionREV.pdf.

Urbanchuk, J. and J. Kapell. “Ethanol and the Local Community” (Mt. Laurel, NJ and Boston: AUS Consultants and SJH & Company, 20 June 2002).

University of Illinois Extension (2005). Cited in M. Kojima and T. Johnson, “Potential for Biofuels for Transport in Developing Countries” (Washington, DC: World Bank, 2005).

Utria, B. Comments made at Biofuels Roundtable, Washington, DC, 7 July 2005.

Utria, B. Senior Economist and Co-Chair of the Energy & Poverty Thematic Group, Energy Unit, Africa Region, World Bank, e-mail to Lauren Sorkin and Suzanne Hunt, Worldwatch Institute, 15 February 2006.

Utria, B. Senior Economist and Co-Chair of the Energy & Poverty Thematic Group, Energy Unit, Africa Region, World Bank World Bank, e-mail to Worldwatch Institute, 21 February 2006.

van den Broek, R. et al. "Potentials for electricity production from wood in Ireland," *Energy*, vol. 26, no. 11 (2001), pp. 991–1013.

Van Dync, D.L. and M.G. Blase. "Cheaper Biodiesel Through a Reduction in Transaction Costs," in proceedings of Bioenergy '98: Expanding Bioenergy Partnerships, available at www.biodiesel.org/resources/reportsdatabase/reports/gen/19981001_gen-109.pdf.

van Ravenswaay, E.O. "Pollution Prevention Case Study on Petroleum" (East Lansing, MI: Michigan State University, 15 October 1998), at www.msu.edu/course/eep/255/PetroleumP2CaseStudy.htm.

Vanguard, "Nigeria's Search for an Alternative to Petrol," *Africa News*, 6 September 2005.

Vereinigten Werkstätten für Pflanzenöltechnologie. Web site, www.pflanzenoel-motor.de.

VIEWLS project. Web site, at www.viewls.org.

Vidal, J. "America's Masterplan is to Force GM Food on the World," *The Guardian*, 13 February 2006.

Vogel, K.P. and R.A. Masters. "Developing Switchgrass into a Biomass Fuel Crop for the Midwestern USA," paper presented at BioEnergy '98: Expanding Bioenergy Partnerships, Madison, WI, 4–8 October 1998.

von Lampe, M. "Agricultural Market Impacts of Future Growth in the Production of Biofuels" (Paris: Organisation for Economic Co-operation and Development, 2006).

von Wedel, R. "Technical Handbook for Marine Biodiesel in Recreational Boats" (Point Richmond, CA: CytoCulture International: Second Edition, 1999), at www.cytoculture.com/Biodiesel%20Handbook.htm.

Wallace, R. et al. "Feasibility Study for Co-Locating and Integrating Ethanol Production Plants from Corn Starch and Lignocellulosic Feedstocks" (Washington, DC: U.S. Deparment of Agriculture and DOE, January 2005).

Walsh, M. et al. "Biomass Feedstock Availability in the United States: 1999 State Level Analysis" (Oak Ridge, TN: Oak Ridge National Laboratory, updated January 2000).

Wang, M. "Greet Model version 1.5a", revision June 2001 (calculations made by IEA for reference case using the downloadable model, in consultation with author), http://greet.anl.gov.

Wang, M. "The Debate on Energy and Greenhouse Gas Emissions Impacts of Fuel Ethanol," presentation to Energy Systems Division Seminar, Argonne National Laboratory, Chicago, IL, 3 August 2005, at www.transportation.anl.gov/pdfs/TA/347.pdf.

Wang, M., C. Saricks, and D. Santini. "Effects of Fuel Ethanol on Fuel-Cycle Energy and Greenhouse Gas Emissions" (Argonne, IL: Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, January 1999).

Waskow, D. International Progam Director, Friends of the Earth-US, Washington, DC, personal communication with L. Sorkin and S. Hunt, 17 February 2006.

Watkins, K. and J. von Braun. "Time to Stop Dumping on the World's Poor," *2002-2003 IFPRI Annual Report* (Washington, DC: International Food Policy Research Institute, 2003).

Werner, C. "Subsidies: Historic, Current and the Skewing of Market Signals," Environmental and Energy Study Institute, presentation to conference, Policy, Institutions and the True Costs of Carbon. Albuquerque, NM, 29 July 2005, at www.eesi.org/publications/Presentations/NCC%20Energy%20Subsidies%207.29.05.pdf.

WestStart-CalStart. "California Biogas Industry Assessment White Paper" (Pasadena, CA: April 2005).

Wiegmann, K. and Fritsche, U.R. and B. Elbersen. "Environmentally Compatible Biomass Potentials in Europe," study sponsored by the EEA (Darmstadt/Wageningen: 2006).

Wiegmann, K. and Fritsche, U.R. with B. Elbersen. "Environmentally Compatible Biomass Potential from Agriculture" (Darmstadt: Öko-Institut, February 2006).

Wiegmann, K. et al. "Environmentally-compatible bioenergy potentials in the EU 25," final report prepared for the European Environment Agency (Darmstadt/Wageningen/Kopenhagen: 2006).

Wilcox, L. "Energy Outlook: Impacts on Biofuels and Implications for the Farm Sector," presentation at 2005 Crop Management Conference, Fapri, Missouri, 14 December 2005, available at www.fapri.missouri.edu/outreach/presentations/2005/cropmang_dec05.pdf.

Wilhelm, W. U.S. Department of Agriculture, Agricultural Research Service, "Sustainability of Crop Residues as Feedstock for Bio-based Products," presentation at the 1st International Biorefinery Workshop, Washington, DC, 20–21 July 2005.

Wilhelm, W.W. and J. Cushman. "Implications of Using Corn Stalks as a Biofuel Source: A Joint ARS and DOE Project," *Eos. Trans. Agu,,* vol. 84, no. 46 (2003), available at ars.usda.gov/research/publications/publications.htm?SEQ_NO_115=166979.

Wilhelm, W.W. et al. "Crop and Soil Productivity Response to Corn Residue Removal: A Literature Review," *Agronomy Journal*, vol. 96, no. 1 (2004), p. 117.

Willams, R.H. "Variants of a low CO2-emitting energy supply system (LESS) for the world," prepared for the IPCC Second Assessment Report Working Group Iia, Energy Supply Mitigation Options (Pacific Northwest Laboratories, 1995).

World Bank Carbon Finance Unit (CFU). Web site, www.carbonfinance.org.

World Bank CFU. "Project Portfolio," at www.carbonfinance.org.

World Economic Forum in Russia. "In-depth: Economic diversification in Russia," World Economic Forum in Russia (Geneva: World Economic Forum, 18 November 2005), at www.weforum.org/site/homepublic.nsf/Content/Report+Russia+2005+-+theme+2.

World Energy Alternatives. "Biodiesel Emissions," at www.worldenergy.net/product/emissions.asp, viewed 29 January 2006.

World Energy Council. "Biomass (Other Than Wood)," in *Survey of Energy Resources 2001* (London: 2001).

World Energy Council, *New Renewable Energy Resources: A Guide to the Future* (London: Kogan Page Ltd., 1994).

World Health Organization, in collaboration with UNEP. *Public Health Impact of Pesticides Used in Agriculture* (Geneva: 1990).

World Petroleum Council. “Exploration and Production in the Marine Environment,” at www.world-petroleum.org/education/exprod/, viewed June 2005.

World Summit on Sustainable Development. “Executive Summary of the Brazilian Energy Initiative,” presented at the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August–4 September, 2002, available at www.worldenergy.org/wec-geis/focus/wssd/goldemberg.pdf

World Trade Organization. “Canada – Certain Measures Affecting the Automotive Industry” (Geneva: 11 February 2001).

World Trade Organization, “European Communities—Measures Affecting Asbestos And Asbestos-Containing Products” (Geneva: 12 March 2001).

World Trade Organization. Web site, at www.wto.org.

Worldwatch Institute. *Vital Signs 2005* (New York: W.W. Norton & Company, 2005).

Wu, S. et al. “Soil Conservation Benefits of Large Biomass Soybean (LBS) for Increasing Crop Residue Cover,” *Journal of Sustainable Agriculture*, vol. 24, no. 1 (2004), pp. 107–128.

Wuppertal Institute for Climate, Environment, and Energy. “Synopsis of German and European Experience and State of the Art of Biofuels for Transport,” prepared for Deutsche Gesellschaft Für Technische Zusammernarbeit (GTZ) GmbH (Wuppertal: July 2005).

www.awknowledge.com. “Ford Launches Focus Flexi-Fuel in UK,” 6 September 2005.

www.int.iol.co.za (South Africa). “Brazil poised to become biodiesel giant,” 19 November 2005.

www.mallenbaker.net. “Companies in Crisis—What Not to Do When It All Goes Wrong: Exxon Mobil and the Exxon Valdez,” at www.mallenbaker.net/csr/CSRfiles/crisis03.html, viewed 4 March 2006.

www.sweedtrack.com. “Reducing our dependence on oil,” at www.sweedtrack.com/eflwa22a.htm.

Yacobucci, B.D. “Ethanol Imports and the Caribbean Basin Initiative” (Washington, DC: Energy Policy Resources, Science, and Industry Division, Congressional Research Service, September 2004), at http://ncseonline.org/NLE/CRSreports/04Sep/RS21930.pdf.

Yamamoto, H. et al. “Evaluation of bioenergy resources with a global land use and energy model formulated with SD technique,” *Applied Energy*, vol. 63 (1999), pp. 101–13.

Yong, W. “Liaoning adopts ethanol gasoline,” *China Daily,* 1 November 2005.

ENDNOTES

Preface

[1] Christoph Berg, Senior Analyst, F.O. Licht, Agra Informa Ltd, Kent, United Kingdom, e-mail to Peter Stair, Worldwatch Institute, 25 January 2006.
[2] "USDA raises corn use estimate for fuel ethanol production," *F.O. Licht World Ethanol & Biofuels Report*, 8 March 2006.
[3] Brazil from Eric Martinot et al., "Renewables 2005: Global Status Report" (Bonn: REN 21, 2005); "EU Rapeoil Selling Out for Biofuel Use," *Oil World*, 19 October 2005; Martin von Lampe, "Agricultural Market Impacts of Future Growth in the Production of Biofuels," (Paris: OECD, 2006), p. 15.

Chapter 1. Current Status of the Biofuel Industry and Markets

[1] More than 90 percent from Christoph Berg, Senior Analyst, F.O. Licht, Kent, United Kingdom, e-mail to Peter Stair, Worldwatch Institute, 25 January 2006.
[2] One-quarter from Christoph Berg, "World Fuel Ethanol Analysis and Outlook" (Kent, United Kingdom: F.O. Licht, April 2004)
[3] Figures 1–1 and 1–2 from Berg, op. cit. note 1. For biodiesel, liters per day is calculated using the approximation that 1,000 liters of biodiesel equals 0.88 tonnes.
[4] Oil growth from Christopher Flavin, "Fossil Fuel Use Surges," in Worldwatch Institute, *Vital Signs 2005* (New York: W.W. Norton & Company, 2005) pp. 30–31; petroleum production data for 2005 from the U.S. Department of Energy (DOE), Energy Information Administration (EIA), *Petroleum Information Monthly*, February 2006.
[5] Production numbers from Berg, op. cit. note 1; gasoline consumption from DOE, EIA, ibid.
[6] Bill Kovarik, "Henry Ford, Charles Kettering and the 'Fuel of the Future,'" *Automotive History Review*, Spring 1998, pp. 7–27, available at www.radford.edu/~wkovarik/papers/fuel.html.
[7] Ibid.
[8] Luiz Carlos Correa Carvalho and Usina Alto Alegre, "Brazil-State of Ethanol Industry," presentation to 1st World Summit on Ethanol for Transportation, Quebec, Canada, 2–4 November 2003.
[9] Berg, op. cit. note 1.
[10] Dehua Liu, "Chinese Development Status of Bioethanol and Biodiesel," presentation at "Biofuels: An Energy Solution," 2005 World Biofuels Symposium, Tsinghua University, Beijing, 13–15 November 2005.
[11]Stephen Karekezi et al., "Traditional Biomass Energy: Improving its Use and Moving to Modern Energy Use," Thematic Background Paper (Bonn: Renewables 2004, January 2004).
[12] Ibid.
[13] Karin Bendz, "EU-25. Oilseeds and Products. Biofuels situation in the European Union 2005," *GAIN Report* (Washington, DC: U.S. Department of Agriculture Foreign Agricultural Service, March 2005).
[14] "Biofuels and the international development agenda," *F.O. Licht's World Ethanol and Biofuels Report*, 8 July 2005.
[15] "Rising ethanol prices may hit Brazilian flex-fuel car sales," *F.O. Licht's World Ethanol and Biofuels Report*, 9 March 2006.
[16] "World ethanol production 2005 to be higher than expected," *F.O. Licht's World Ethanol and Biofuels Report*, 24 October 2005.
[17] Ibid.; Marla Dickerson, "Brazil's Ethanol Effort Helping Lead to Oil Self-Sufficiency," *Los Angeles Times*, 17 June 2005. Table 1–1 from F.O. Licht, cited in Renewable Fuels Association, *Homegrown for the Homeland: Industry Outlook 2005* (Washington, DC: 2005).
[18] F.O. Licht, ibid., p. 14.
[19] Ibid.
[20] Berg, op. cit. note 2.

[21] Renewable Fuels Association (RFA), "From Niche to Nation: Ethanol Industry Outlook 2006" (Washington, DC: February 2006).
[22] Table 1–2 from Berg, op. cit. note 1.
[23] Figure of 80 percent of biofuel production from Bendz, op. cit. note 13; 88.6 percent from Berg, op. cit. note 1.
[24] Berg, op. cit. note 1; National Biodiesel Board, "Biodiesel Production Soars," press release (Jefferson City, MO: 8 November 2005).
[25] Tom Bryan, "Editor's note regarding total biodiesel production capacity in the U.S., *Biodiesel Magazine*, October 2005; Berg, op. cit. note 1.
[26] Price of crude oil from DOE, EIA, "West Texas Intermediate Crude Oil Price," in *Short-Term Energy Outlook* (Washington, DC: March 2006), at www.eia.doe.gov/emeu/steo/pub/gifs/Slide2.gif
[27] DOE, EIA, *Annual Energy Outlook* (Washington, DC: December 2005).
[28] DOE, EIA, op. cit. note 4, at www.eia.doe.gov/emeu/ipsr/t46.xls.
[29] DOE, EIA, op. cit. note 27.
[30] "World Ethanol Production 2005 to be Higher Than Expected," *F.O. Licht's World Ethanol and Biofuels Report*, 24 October 2005.
[31] Bendz, op. cit. note 13.
[32] "World ethanol production 2005 to be higher than expected," op cit. note 16.
[33] Ibid.
[34] Ibid.
[35] Sidebar 1–1 from F. Kaltner et al., "Biofuels for Transportation: Brazilian Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Rio de Janeiro: November 2005).
[36] "World ethanol production 2005 to be higher than expected," op cit. note 16.
[37] Ibid.
[38] Ibid.
[39] Boris Utria, World Bank, e-mail to Worldwatch Institute, 21 February 2006.
[40] South Africa also makes extensive use of F-T technology; however, to date it has mostly used it to produce fuel from coal.
[41] Novozymes, "Novozymes and NREL reduce enzyme cost," press release (Bagsvaerd, Denmark: 14 April 2005); Abengoa Bioenergy, "Abengoa Bioenegy R&D's first pilot plant is ready to begin research and development operations," feature story, at www.abengoabioenergy.com/feature.cfm?page=6.

Chapter 2. Liquid Biofuels—A Primer

[1] S.W. Mathewson, "Yeast and Fermentation," in *The Manual for the Home and Farm Production of Alcohol Fuel* (Berkeley, CA: Ten Speed Press, 1980).
[2] F. Kaltner et al., "Biofuels for Transportation: Brazilian Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Rio de Janeiro: November 2005), p. 23.
[3] National Science-Technology Roadshow Trust, "Morton Coutts—Continuous Fermentation System," at www.roadshow.org/html/resources/scientists/coutts/article.html, viewed 29 January 2006.
[4] J.N. de Vasconcelos, "Continuous Ethanol Production Using Yeast Immobilized on Sugar Cane Stalks," *Brazilian Journal of Chemical Engineering*, July/September 2004; J. Goldemberg and I. Macedo, "Brazilian Alcohol Program: An Overview," in International Energy Agency, *Energy for Sustainable Development* (Paris: May 1994).
[5] Genencor International, "Transforming the Ethanol Industry" (Palo Alto, CA: June 2005); V. Singh et al., "Modified Dry Grind Ethanol Process" (Champaign, IL: University of Illinois at Urbana-Champaign Agricultural Engineering Department, 18 July 2001); U.S. National Renewable Energy Laboratory (NREL), "The Biomass Economy," *National Renewable Energy Laboratory 2002 Research Review*, July 2002.
[6] M. Paster, J. Pellegrino, and T. Carole, "Industrial Bioproducts: Today and Tomorrow," prepared by Energetics, Inc., for the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, Office of the Biomass Program (Washington, DC: July 2003).

[7] A. McAloon et al., "Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks" (Golden, CO: U.S. Department of Agriculture Agricultural Research Service and NREL-Biotechnology Center for Fuels and Chemicals, October 2000).
[8] "Corn Wet Milling Industry Faces Many Challenges in Current Global Environment, Says New Analysis," *Business Wire*, 13 January 2006; NREL, op. cit. note 5.
[9] J. Ashworth et al., *Properties of Alcohol Transportation Fuels*, prepared for DOE by Meridian Corporation (Washington, DC: May 1991).
[10] N. Schmitz et al., eds., *Innovationen bei der Bioethanolerzeugung. Schriftenreihe, Nachwachscende Rohstoffe. Gand 26*. (Bonn: German Federal Ministry of Food, Agriculture and Consumer Protection and Germany Agency of Renewable Resources, 2005).
[11] NREL, op. cit. note 5.
[12] Edgar Remmele, "Position Paper: Technologie-und Forderzentrum im Kimpetenzzentrum fur Nachwachsende Rohstoffe," 2004, p. 5, cited in Wuppertal Institute for Climate, Environment, and Energy, "Synopsis of German and European Experience and State of the Art of Biofuels for Transport" (Wuppertal: July 2005)
[13] Ibid.
[14] Howard Haines, Montana Department of Natural Resources, personal communication with Worldwatch Institute, 14 December 2005.
[15] Wuppertal Institute for Climate, Environment, and Energy, op. cit. note 12. For the German filter exchange program, see www.pflanzenoel-motor.de.
[16] J.A. Kinast, "Properties of Biodiesels and Biodiesel/Diesel Blends," Pprepared by Gas Technologies Institute for NREL (Golden, CO: March 2003), p. 2.
[17] National Biodiesel Board, "Biodiesel Production and Quality Standards," fact sheet (Jefferson City, MO: updated 11 March 2002), at www.biodiesel.org/pdf_files/fuelfactsheets/prod_quality.pdf.
[18] National Biodiesel Board, "Biodiesel Production," fact sheet (Jefferson City, MO: updated 29 January 2005), at www.biodiesel.org/pdf_files/fuelfactsheets/Production.pdf.
[19] A. Radich, "Biodiesel Performance, Costs, and Use" (Washington, DC: DOE, Energy Information Administration (EIA), updated 8 June 2004, at www.eia.doe.gov/oiaf/analysispaper/biodiesel; AEA Technology, "Appendix 3: Potential for Production Cost Reduction," in *International Resource Costs of Biodiesel and Bioethanol*, prepared for the UK Department for Transport (London: 2003).
[20] NREL, op. cit. note 5, p. 2.
[21] Organisation for Economic Co-operation and Development (OECD), "Agricultural Market Impacts of Future Growth in the Production of Biofuels" (Paris: OECD Working Party on Agricultural Policies and Markets, 2006); Lew Fulton, Sustainable Transport, Division of Global Environment Facility Coordination, United Nations Environment Programme, e-mail to Peter Stair, Worldwatch Institute, July 2005.
[22] Michael Hogan, "German Biodiesel Sales Strong as Oil Prices Rise," *Reuter*s, 19 August 2005.
[23] Table 2–1 from OECD, op. cit. note 21.
[24] Radich, op. cit. note 19.
[25] Figures 2–1 and 2–2 based on the following sources: Lew Fulton et al., *Biofuels for Transport: An International Perspective* (Paris: International Energy Agency, 2004); Timothy Gardner, "Can Fungi Trim the US Gasoline Habit?" *Reuters*, 27 February 2006**;** DOE, EIA Energy StatisticsWeb site, at www.eia.doe.gov/emeu/international/oilprice.html, viewed February 2006.
[26] Cost data for dry-mill and wet-mill co-products from Fulton et al., ibid. "Corn Wet Milling Industry Faces Many Challenges in Current Global Environment, Says New Analysis," op. cit. note 8; NREL, op. cit. note 5.
[27] Isaias de Carvalho Macedo et al., "Sugar Cane's Energy: Twelve Studies on Brazilian Sugar Cane Agribusiness and Its Sustainability" (São Paolo: União da Agroindústria Canavieira de São Paulo, September 2005), p. 186.
[28] Novozymes & BBI International, "Fuel Ethanol: A Technological Evolution" (Grand Forks, ND: June 2005).

Chapter 3. First-Generation Feedstock

[1] Table 3–1 from Lew Fulton et al., *Biofuels for Transport: An International Perspective* (Paris: International Energy Agency, 2004) and from F. Kaltner et al., "Liquid Biofuels for Transportation in Brazil:

Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Rio de Janeiro: November 2005).
[2] Figure 3–1 from Fulton et al., ibid.
[3] F. Kaltner et al., op. cit. note 1.
[4] Isaias de Carvalho Macedo et al., "Sugar Cane's Energy: Twelve Studies on Brazilian Sugar Cane Agribusiness and Its Sustainability" (São Paolo: União da Agroindústria Canavieira de São Paulo, September 2005).
[5] Ibid.
[6] U.N. Food and Agriculture Organization (FAO) and International Institute for Applied Systems Analysis (IIASA) *Global Agro-Ecological Zones (Global-AEZ)*, CD-ROM (Rome and Laxenburg, Austria: 2000), at www.fao.org/landandwater/agll/gaez/index.htm.
[7] Table 3–2 from U.S. Department of Agriculture (USDA), Foreign Agricultural Service (FAS), "Production, Supply & Distribution database,"available at www.fas.usda.gov/psd/complete_files/HTP-0612000.csv.
[8] FAO, FAOSTAT electronic database, at http://faostat.fao.org.
[9] Illovo Sugar, "World of Sugar: International Sugar Statistics," 2005, awww.illovo.co.za/worldofsugar/internationalSugarStats.htm, viewed 12 March 2006.
[10] Net for Cuba International, "A Brief on the Industrial Sector for Cuba," www.netforcuba.org/InfoCuba-EN/Economy/ABrief.htm, viewed 12 March 2006.
[11] C. Strossman, "European Union Sugar Annual 2004," *GAIN Report* (Washington, DC: USDA, FAS, 8 April 2004. Tonnes of total sugar beets harvested are calculated based on the assumption of 18 percent raw sugar content in the harvested sugar beet roots/plants.
[12] Hosein Shapouri, Senior Economist, USDA, conversation with Peter Stair, 15 December 2005.
[13] "Commission cuts sugar quotas for 2006/07," *F.O. Licht's World Ethanol and Biofuels Report*, 8 March 2006.
[14] Jason Clay, *World Agriculture and Environment* (Washington, DC: Island Press, 2004), p. 412.
[15] Renewable Fuels Association (RFA), "Homegrown for the Homeland: Ethanol Industry Outlook 2005" (Washington, DC: February 2005).
[16] Danielle Murray, "Ethanol's Potentail: Looking Beyond Corn," Eco-Economy Update (Washington, DC: Earth Policy Insitute, 29 June 2005).
[17] Fulton et al., op. cit. note 1.
[18] FAO, op. cit. note 8.
[19] Average wheat yields from FAO (2002), cited in Leonard Gianessi, Sujatha Sankula, and Nathan Reigner, "Plant Biotechnology: Potential Impact for Improving Pest Management in European Agriculture: Herbicide Tolerant Wheat Case Study" (Washington, DC: National Center for Food & Agricultural Policy, December 2003).
[20] W. Bushuk, "Rye Production and Uses Worldwide," *Cereal Foods World*, vol. 6, no. 2 (2005); Peter Talks, "EU-25 Grain and Feed Semi-Annual 2004," *GAIN Report* (Washington, DC: USDA, FAS, 8 December 2004).
[21] FAO, "Proceedings of the Validation Forum on the Global Cassava Development Strategy," Rome, 26–28 April, 2000, at www.fao.org/documents/show_cdr.asp?url_file=/docrep/007/y2413e/y2413e07.htm.
[22] "Thailand looking to import ethanol to mix with petrol," *The Bangkok Post*, 5 September 2005; Vanguard, "Nigeria's Search for Alternative to Petrol," *Africa News,* 6 September 2005
[23] FAO, op. cit. note 8.
[24] Table 3–3 from USDA FAS, "Counselor and Attache Reports Official Statistics, Estimates for March 2004/2005, (Washington, DC: Cotton, Oilseeds, Tobacco and Seeds Division, March 2006), at www.fas.usda.gov/oilseeds/circular/2006/06-03/table1t3.pdf.
[25] Figure 3–2 from Kaltner et al., op. cit. note 1, p. 24.
[26] J. Gerpen, D. Clements, and G. Knothe, "Biodiesel Production Technology: August 2002—January 2004" (Golden, CO: National Renewable Energy Laboratory (NREL), June 2004).
[27] Average rapeseed yields from USDA, FAS, "Oilseeds: World Markets and Trade," Circular Series FOP106 (Washington, DC: January 2006); agricultural practices from Wuppertal Institute for Climate, Energy, Environment, "Synopsis of German and European Experience and State of the Art of Biofuels for Transport," prepared for GTZ (Wuppertal: July 2005); rapeseed yields from Martin Bensmann, "Bio im Tank," *Neue Energie*, vol. 3 (2005).
[28] FAO, op. cit. note 8.

[29] Stat Communications, "Biodiesel lifts German rapeseed area," statpub.com, 21 February 2006, at www.statpub.com/open/183421.phtm.
[30] "German winter rapeseed plantings rise on biodiesel demand," *F.O. Licht's World Ethanol and Biofuels Report*, 3 February 2006.
[31] Table 3–4 from FAO, Statistics Division, "Major Food and Agricultural Commodities and Producers," at www.fao.org/es/ess/top/commodity.jsp?commodity=270&lang=EN&year=2004.
[32] Jane Earley, Thomas Earley, and Matthew Straub, "Specific Environmental Effects of Trade Liberalization: Oilseeds" (Washington, DC: International Policy Council for Food and Agriculture, October 2005), p. 5.
[33] FAO, op. cit. note 8.
[34] Kaltner et al., op. cit. note 1.
[35] Helen Buckland, "The Oil for Ape Scandal: How palm oil is threatening the orangutan" (London: Friends of the Earth-UK, 2004), www.foe.co.uk/resource/reports/oil_for_ape_summary.pdf; Roundtable on Sustainable Palm Oil, "The Malaysian Palm Oil Association (MPOA)" (Singapore: 2005), at www.sustainable-palmoil.org/profile.htm.
[36] K.S. Sethi, "Biofuels 2012: Vision to Reality," Planning Commission, 2003, www.teriin.org/events/docs/5biofuel.htm, viewed 18 October 2005.
[37] D1 Oils, "The Birth of a Global Biodiesel Business," at www.d1plc.com/about/history.php, viewed 12 March 2006.
[38] R. Mandal, "The Indian Biofuels Programme—National Mission on Bio-diesel," presentation at the International Conference and Expo, Biofuels 2012: Vision to Reality, New Delhi, 17–18 October 2005.
[39] European Biomass Industry Association, "Biodiesel," *Biofuels for Transport*, at http://p9719.typo3server.info/214.0.html, viewed 12 March 2006
[40] USDA, FAS, op. cit. note 7, updated January 2006.
[41] NREL, Mustard Seed Research Program presentation (Golden, CO: March 2002), at www.nrel.gov/docs/gen/fy02/31794.pdf.
[42] Government of the Philippines, "DOE identifies alternative fuel sources (Philippines)" (Manila: 26 August 2005), at www.pia.gov.ph/news.asp?fi=p050826.htm&no=16.
[43] Kaltner et al., op. cit. note 1, pp. 6, 57; Multi-commodity Exchange of India, Ltd., "Castor Oil Profile," at www.mcxindia.com/castor_oil.aspx, viewed 14 March 2006.
[44] W. Gehua et al., "Liquid Biofuels for Transportation: Chinese Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for GTZ (Beijing: September 2005), p. 16.
[45] Kaltner et al., op. cit. note 1; The Energy and Resources Institute (TERI), "Biofuel for Transportation: India Country Study on Potential and Implications for Sustainable Agriculture and Energy," prepared for GTZ (New Delhi: October 2005).
[46] Subramanian et al. (2005) and Azam et al. (2005), cited in ibid.
[47] John Sheehan et al., "A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae" (Golden, CO: NREL, 1998).
[48] "Algae—like a breath of mint for smokestacks," *USA Today*, 10 January 2006; GreenFuel Technologies Corporation Web site, at www.greenfuelonline.com/index.htm.
[49] Ibid.
[50] Sheehan et al., op. cit. note 47.
[51] Kaltner et al., op. cit. note 3, p. 37.
[52] Ibid.
[53] Figure 3–3 from Organisation for Economic Co-operation and Development (OECD), "Agricultural Market Impacts of Future Growth in the Production of Biofuels" (Paris: OECD Working Party on Agricultural Policies and Markets, 2006).
[54] RFA, op. cit. note 15.
[55] FAO and IIASA, op. cit. note 6.
[56] Jose Roberto Moreira, "Global Biomass Energy Potential" (São Paulo: CENIBO, 2004).
[57] Fulton et al., op. cit. note 1, p. 18.
[58] EU Rapeoil Selling out for Biofuel use," *Oil World*, 19 October 2005.
[59] Michael C. Sutton, Nicole Klein, and Gary Taylor, "A Comparative Analysis of Soybean Production Between the United States, Brazil, and Argentina," *Journal of the American Society of Farm Managers and Appraises,* 2005, at www.asfmra.org/documents/Sutton33_41.pdf.
[60] Wuppertal Institute for Climate, Environment, and Energy, op. cit. note 27.

[61] Corn from University of Illinois Extension (2005), cited in Masami Kojima and Todd Johnson, "Potential for Biofuels for Transport in Developing Countries" (Washington, DC: World Bank, 2005); soy and oil palm from Clay, op. cit. note 13, pp. 176–177, 211.
[62] Table 3–5 is based on the following sources: Brazil sugarcane from Schmitz et al. (2002), cited in Kojima and Johnson, ibid; corn from University of Illinois Extension (2005), cited in idem; Brazil soy and oil palm from Clay, op. cit. note 13, pp. 176–177, 211; U.S. soy from National Biodiesel Board, "Biodiesel as a Greenhouse Gas Reduction Option" (Jefferson City, MO: 2004), at www.biodiesel.org/resources/reportsdatabase/reports/gen/20040321_gen-332.pdf.
[63] Robert Perlack et al., "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion Ton Annual Supply" (Oak Ridge, TN: Oak Ridge National Laboratory, April 2005).
[64] National Corn Growers Association, "The World of Corn 2004," at http://ncga.com/ WorldOfCorn/main.
[65] Sidebar 3–1 is based on the following sources: yield increases from Angelo Bressan Filho, Director of AgroEnergy Program, Brazilian Ministry of Environment, "The AgriEnergy Option for the Future," presentation at the Workshop and Business Forum on Sustainable Biomass Production for the World Market, São Paulo, Brazil, 30 November–2 December 2005; plant varieties, planted acerage, and industry involvement from Kaltner et al., op. cit. note 1, p. 42.
[66] European and German crop yield trends from R. Edwards et al., "Well-to-wheel analysis of future automotive fuels and power trains in the EU context, well-to-tank report" (Brussels: CONCAWE, EUCAR, 2003), p. 25 and from Martin Kaltschmitt et al., "Analyse und Bewertung der Nutzungsmöglichkeiten von Biomasse–Arbeitspaket des IE Leipzig," In Vorbereitung (Leipzig: 2005), p. 18; U.S. corn crop yields from A. Dobermann et al., "Understanding and Managing Corn Yield Potential," in *Proceedings of the Fertilizer Industry Round Table, Charleston, SC, 28-30 October 2002* (Forest Hill, MD: The Fertilizer Industry Round Table); biotech hybrid corn yields from National Corn Growers Association, op. cit. note 64; continued development from Fulton et al., op. cit. note 1, pp. 65–66; National Biodiesel Board, op. cit. note 62, p. 2.

Chapter 4. Next-Generation Feedstock

[1] Table 4–1 from Jonathan Scurlock, *Bioenergy Feedstock Characteristics* (Oak Ridge, TN: Oak Ridge National Laboratory, 2000).
[2] Table 4–2 from the following sources: ibid.; Thomas P.E. Miles et. al., "Alkali Deposits Found in Biomass Power Plants: A Preliminary Investigation of Their Extent and Nature" (National Renewable Energy Laboratory (NREL), 15 April 1995); Ralph Hollenbacher, "Biomass Combustion Technologies in the United States," paper presented at the Biomass Combustion Conference, Reno, NV, 28–29 January 1992; Thomas Miles, Sr., "Operating Experience with Ash Deposition in Biomass Combustion Systems, Biomass Combustion Conference, Reno, NV, 28–29 January1992; Thomas Milne et al., "Thermodynamic Data for Biomass Conversion and Waste Incineration" (Golden, CO: Solar Energy Research Institute (now NREL), September 1986); Paul Gallegeher, U.S. Department of Energy (DOE), "Biomass Feedstock Composition and Property Database," January 2006, at www1.eere.energy.gov/biomass/feedstock_databases.html.
[3] M. Hoogwijk et al., "Exploration of the ranges of the global potential of biomass for energy," *Biomass and Bioenergy*, vol. 25, no.2 (2003), pp. 119–33.
[4] For an overview of biomass characteristics, see A. Faaij et al., "Characteristics and availability of biomass waste and residues in the Netherlands for gasification," *Biomass and Bioenergy*, vol. 12, no. 4 (1997), pp. 225–40.
[5] DOE, "Black Liquor Gasification Expected to Yield Energy, Environmental, and Environmental Benefits" (Washington, DC: Fall 2001), at www1.eere.energy.gov/industry/bestpractices/fall2001_black_liquor.html.
[6] Table 4–3 from Philippe Girard, Abigail Fallot, and Fabien Dauriac, "Biofuels Technology: State-of-the-Art," prepared for the Global Environment Facility (UNEP/GEF) Technical Workshop on Liquid Biofuels, New Delhi, India, 29 August–1 September 2005.
[7] Conservation Technology Information Center (CTIC), "Conservation Tillage and Other Tillage Types In the United States–1990-2004," *National Crop Residue Management Survey*, at www.ctic.purdue.edu/Core4/CT/CT.html; Robert Perlack et al., "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: the Technical Feasibility of a Billion Ton Annual Supply" (Washington, DC: DOE and U.S. Department of Agriculture, April 2005).

[8] W.W. Wilhelm et al., "Crop and Soil Productivity Response to Corn Residue Removal: A Literature Review," *Agronomy Journal*, vol. 96, no. 1 (2004), p. 117.
[9] F. Kaltner et al., **"**Liquid Biofuels for Transportation in Brazil: Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Rio de Janeiro: November 2005).
[10] Ibid.
[11] Ibid.
[12] Figure 4–1 from Perlack et al., op. cit. note 7, p. 21.
[13] Ibid.
[14] DOE, "Roadmap for Agriculture Biomass Feedstock Supply in the United States" (Washington, DC: November 2003); Wilhelm et al., op. cit. note 8.
[15] Perlack et al., op. cit. note 7. Sidebar 4–2 is based on the following sources: T.E. Devine and E. O. Hatley, "Registration of 'Donegal' Forage Soybean," *Crop Science*, vol. 38 (1998), pp. 1719–20; T.E. Devine, E. O. Hatley, and D. E. Starner, "Registration of 'Derry' Forage Soybean," *Crop Science*, vol. 38 (1998), p. 1719; T.E. Devine, E. O. Hatley, and D. E. Starner, "Registration of 'Tyrone' Forage Soybean." *Crop Science*, vol. 38 (1998), p. 1720; T. Devine and J. E. McMurtrey III, "Registration of "Tara" Soybean," *Crop Science*, vol. 44 (2004, p. 1020; S. Wu et al., "Soil Conservation Benefits of Large Biomass Soybean (LBS) for Increasing Crop Residue Cover," *Journal of Sustainable Agriculture*, vol. 24, no. 1 (2004), pp. 107–128**.**
[16] Larcio Couto and David R. Betters, "Short Rotation Eucalypt Plantations in Brazil: Social and Environmental Issues" (Oak Ridge, TN: Oak Ridge National Laboratory, February 1995).
[17] G.W. Burton, "Improved recurrent restricted phenotypic selection increases bahiagrass forage yields," *Crop Science,* vol. 22 (1982), pp. 1058–61; G.W. Burton and B.G. Mullinix, "Yield distributions of spaced plants within Pensacola bahiagrass populations developed by recurrent restricted phenotypic selection," *Crop Science*, vol. 38 (1988), pp. 333–36, cited in Nathanael Greene et al., "Growing Energy: How Biofuels Can Help End America's Oil Dependence" (Washington, DC: Natural Resources Defense Council, December 2004), p. 26.
[18] K.P. Vogel and R.A. Masters, "Developing Switchgrass into a Biomass Fuel Crop for the Midwestern USA," paper presented at BioEnergy '98: Expanding Bioenergy Partnerships, Madison, WI, 4–8 October 1998.
[19] D.S. Powlson, A.B. Riche, and I. Shield, "Biofuels and Other Approaches for Decreasing Fossil Fuel Emissions from Agriculture," *Annals of Applied Biology*, vol. 146 (2005), pp. 193–201; Lew Fulton et al., *Biofuels for Transport*: *An International Perspective* (Paris: International Energy Agency, 2004), p. 136; André P.C. Faaij, "Bio-energy in Europe: Changing Technology Choices," *Energy Policy* (Special Issue on Renewable Energy in Europe), February 2006, pp. 322–42; Greene et al., op. cit. note 17, p. 26.
[20] R. van den Broek et al., "Potentials for electricity production from wood in Ireland," *Energy*, vol. 26, no. 11 (2001), pp. 991–1013.
[21] Table 4–4 is based on the following sources: van den Broek, ibid; E.E. Biewinga and G. van der Bijl, "Sustainability of energy crops in Europe, a methodology developed an applied," CLM 234-1996 (Utrecht: Centre for Agriculture and Environment, February 1996); V. Dornburg, J. van Dam, and A. Faaij, "Estimating GHG emission mitigation supply curves of large scale biomass use on a country level," *Biomass & Bioenergy*, September 2004; P. Borjesson, "Environmental Effects of Energy Crop Cultivation in Sweden," *Biomass and Bioenergy*, vol. 16 (1999), pp. 137–54; D.O. Hall et al., "Biomass for Energy Supply Prospects," in T.B. Johansson et al., eds., *Renewable Energy—Sources of Fuels and Electricity* (Washington, DC: Island Press, 1993).

Chapter 5. New Technologies for Converting Biomass into Liquid Fuels

[1] P. McKendry, "Energy Production from Biomass (Part 3): Gasification Technologies," *Bioresource Technology*, vol. 83 (2002), pp. 55–63.
[2] Mark Laser and Lee Lynd, Thayer School of Engineering, Dartmouth College, report to Worldwatch Institute, 13 January 2006.
[3] Ibid.
[4] Figure 5–1 from Darmouth College and Natural Resources Defense Council (NRDC), "The Role of Biomass in America's Energy Future (RBAEF)," sponsored by DOE, the Energy Foundation, and the National Commission on Energy Policy, project Web site at

http://engineering.dartmouth.edu/other/rbaef/index.shtml.
[5] Ibid.
[6] Ibid.
[7] Andre Faaij, "Bioenergy in Europe: Changing Technology Choices," *Energy Policy*, 5 December 2003; M. Kaltschmitt, C. Rosch, and L Dinkelbach, eds., "Biomass Gasification in Europe," prepared for the European Commission (Stuttgart: Institute of Energy Economics and the Rational Use of Energy (IER), University of Stuttgart, October 1998).
[8] Mark Laser, Research Associate, Thayer School of Engineering, Dartmouth College, e-mail to Jim Easterly, Easterly Consulting, 2 March 2006.
[9] C.N. Hamelinck and A.P.C. Faaij, "Future Prospects for Production of Methanol and Hydrogen from Biomass," *Journal of Power Sources*, vol. 111 (2002), pp. 1–22.
[10] Laser and Lynd, op. cit. note 2.
[11] Ibid.
[12] A.V. Bridgwater, "Principles and Practice of Biomass Fast Pyrolysis Processes for Liquids," *Journal of Analytical and Applied Pyrolysis*, vol. 51 (1999), pp. 3–22.
[13] S. Czernik and A.V. Bridgwater, "Overview of Applications of Biomass Fast Pyrolysis Oil," *Energy & Fuels*, vol. 18 (2004), pp. 590–98.
[14] DynaMotive Energy Systems Corporation Web site, at www.dynamotive.com.
[15] BTG Biomass Technology Group, BV Web site, at www.btgworld.com.
[16] E. Dinjus and A. Kruse, "Hot compressed water—a suitable and sustainable solvent and reaction medium?" *J. Phys.: Condens. Matter*, vol. 16 (2004), pp. S1161–69.
[17] U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), "Pyrolysis and Other Thermal Processing" (Washington, DC: 2005), at www1.eere.energy.gov/biomass/pyrolysis.html.
[18] J.E. Naber and F Goudriaan, "HTU Diesel," presented at Biofuel BV, Berlin, November 2003.
[19] DOE, "Dilute Acid Hydrolysis" at www.eere.doe.gov/biomass/dilute_acid.html, viewed 16 May 2005.
[20] Arkenol Web site, at www.arkenol.com, viewed 12 January 2006.
[21] Laser and Lynd op. cit. note 2.
[22] P.C. Badger, "Ethanol from cellulose: A general review," in J. Janick and A. Whipkey, eds., *Trends in New Crops and New Uses* (Alexandria, VA: ASHS Press, 2002), pp. 17–21.
[23] Laser, op. cit. note 8.
[24] Novozymes & BBI International, "Fuel Ethanol: A Technological Evolution" (Grand Forks, ND: June 2005).
[25] Laser and Lynd, op. cit. note 2.
[26] Enteric bacteria from L.O. Ingram et al.,"Metabolic engineering of bacteria for ethanol production," *Biotechnology and Bioengineering*, vol. 58, no. 2–3 (1998), pp. 204–12 and from L.O. Ingram et al. "Enteric bacterial catalysts for fuel ethanol production," *Biotechnology Progress*, vol.15, no.5 (1999), pp. 855–66; thermophilic bacteria from S.G. Desai, M.L. Guerinot, and L.R. Lynd, "Cloning of L-lactate *dehydrogenase and elimination of lactic acid production via gene knockout in Thermoanaerobacterium* saccharolyticum," *Applied Microbiology and Biotechnology*, vol. 65, no. 5 (May 1999), pp. 600–05 and from B.K. Ahring et al., "Pretreatment of wheat straw and conversion of xylose and xylan to ethanol by thermophilic anaerobic bacteria," *Bioresource Technology*, vol. 58, no.2 (1996), pp. 107–13; mesophylic bacterium from L.O. Ingram et al., "Enteric bacterial catalysts for fuel ethanol production," op. cit. this note and from R.J. Bothast et al., "Fermentations with new recombinant organisms*," Biotechnology Progress*, vol. 15, no. 5 (1999), pp. 867–75; yeast from N. W. Z. Ho, Z. Chen, and A.P. Brainard, "Genetically engineered *Saccharomyces* yeast capable of effective cofermentation of glucose and xylose," *Applied and Environmental Microbiology*, vol. 64, no.5 (1998), pp. 1852–59 and from S. Sanchez et al., "The fermentation of mixtures of D-glucose and D-xylose by *Candida shehatae*, Pichia stipitis or *Pachysolen tannophilus* to produce ethanol," *Journal of Chemical Technology and Biotechnology*, vol. 77, no. 6 (2002), pp. 641–48.
[27] Timothy Gardner, "Can Fungi Trim the US Gasoline Habit?," *Reuters*, 27 February 2006**.**
[28] Franz J. Kaltner et al., "Liquid Biofuels for Transportation in Brazil: Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Rio de Janeiro: 2005).
[29] DOE, "DOE Announces $160 million for biorefinery contruction," press release (Washington, DC: 22 February 2006).

[30] European Commission (EC), "EU Biomass Action Plan" (Brussels: February 2006).
[31] Figures 5–2 and 5–3 from Lew Fulton et al., *Biofuels for Transport: An International Perspective* (Paris: International Enrgy Agency, 2004).
[32] DOE, EERE, "Novozymes and NREL cut cost of converting biomass to ethanol," *EERE Network News*, 20 April 2005; Genencor, "Genencor Celebrates Major Progress in the Conversion of Biomass to Ethanol," press release (Palo Alto, CA: 21 November 2004); Gardner, op. cit. note 26**.**
[33] L.R. Lynd et al., "Consolidated Bioprocessing of Lignocellulosic Biomass: An Update," *Current Opinion in Biotechnology*, vol. 16 (2005), pp. 577–83.
[34] N.C. Mosier et al., "Features of promising technologies for pretreatment of lignocellulosic biomass," *Bioresource Technology*, vol. 96, no. 6 (2005), pp. 673–86; M.E. Himmel et al., "Advanced Bioethanol Production Technologies: A Perspective. *ACS Symposium Series*, vol. 666 (1997), p. 45
[35] DOE, EERE, "Pretreatment Technology Evaluation", at www1.eere.energy.gov/biomass/technology_evaluation.html , viewed 16 May 2005.
[36] Uwe Fritsche, Öko-Institut, e-mail to Suzanne Hunt, Worldwatch Institute, 13 March 2006.
[37] C. Hamelinck, "Outlook for Advanced Biofuels" (Utrecht: Utrecht University, 7 June 2004).
[38] Rudloff, Matthias, "Biomass-to-Liquid Fuels (BtL)—Made by CHOREN. Process, Environmental Impact and Latest Developments," presentation at the Automobile & Environment at Belgrade EAEC Congress, May 2005.
[39] Frank Seyfried, "RENEW – Renewable Fuels for Advanced Powertrains," 1st Year Report for EU 6th Framework Integrated Project, 2005, available at www.renew-fuel.com.
[40] EC, "Biomass Electricity—Technical Development Status" (Brussels: 2006), at http://europa.eu.int/comm/energy_transport/atlas/htmlu/bioetech.html.
[41] L. Devi, K.J. Ptasinski, and F.J.J.G. Janssen, "A review of the primary measures for tar elimination in biomass gasification processes," *Biomass and Bioenergy*, vol. 24 (2003), pp.125–40; M. Mozaffarian and R.W.R. Zwart, "Feasibility of Biomass/Waste-Related SNG Production Technologies," Novem Project No. 249-01-03-12-0001 (The Hague: Dutch Ministry of Economic Affairs, 2003).
[42] U.S. National Renewable Energy Laboratory (NREL),"Thermochemical Conversion Technologies-Projects," at www.nrel.gov/biomass/proj_thermochemical_conversion.html, viewed 16 May 2005.
[43] Ibid.
[44] DOE, National Energy Technology Laboratory, "Current Industry Perspective: Gasification, World Survey Results 2004" (Pittsburgh, PA: 2005), at www.netl.doe.gov/publications/brochures/pdfs/Gasification_Brochure.pdf; Novozymes & BBI International, "Fuel Ethanol: A Technological Evolution" (Grand Forks, ND: June 2005).
[45] Hamelinck, op. cit. note 37.
[46] Naber and Goudriaan, op. cit. note 18.
[47] Changing World Technologies Web site, at www.changingworldtech.com, viewed 12 January 2006.
[48] Fritsche, op. cit. note 36.
[49] Carlo N. Hamelinck and André Faaij, "Outlook for Advanced Biofuels," *Energy Policy*, 2005**.**
[50] Gardner, op. cit. note 27.
[51] DOE, EERE, op. cit. note 32.
[52] Russel Heisner, BC International, conversation with Peter Stair, Worldwatch Institute, 24 August 2005; "Biomass-to-Ethanol Technology Could Help Replace Half of Auto Fuel in U.S," autospectator.com, posted 22 May 2005.
[53] Laser and Lynd, op. cit. note 2.
[54] Fritsche, op. cit. note 36.
[55] See Sino-German Workshop on Energetic Utilization of Biomass, Beijing, 8–11 October 2003, at www.ipe.ac.cn/sinogerman/program.htm.
[56] "DynaMotive to Make BioOil in Ukraine and Baltic States," RenewableEnergyAccess.com, 31 January 2006.
[57] R. Wallace et al., "Feasibility Study for Co-Locating and Integrating Ethanol Production Plants from Corn Starch and Lignocellulosic Feedstocks" (Washington, DC: U.S. Deparment of Agriculture and DOE, January 2005).
[58] Fritsche, op. cit. note 36.
[59] Darmouth College and NRDC, op. cit. note 4.
[60] Figure 5–4 from Darmouth College and NRDC, op. cit. note 4.

[61] Assumes an 8 percent efficiency benefit for ethanol-optimized engines relative to gasoline engines, per Dr. Tom Kenney, Ford Motor Co., personal communication, 2005
[62] Laser and Lynd, op. cit. note 2.
[63] Ibid.
[64] NatureWorks, LLC Web site, at www.natureworksllc.com, viewed 14 November 2005.
[65] Darmouth College and NRDC, op. cit. note 4.
[66] Fritsche, op. cit. note 36.

Chapter 6. Long-Term Biofuel Production Potentials

[1] Eric Martinot et al., "Renewables 2005: Global Status Report" (Bonn: Renewable Energy Policy Network for the 21st Century (REN21), 2005)
[2] Andre Faaij, Copernicus Institute, Utrecht University, report submitted to Worldwatch Institute, 17 January 2005.
[3] Figure 6–1 from Goran Berndes et al., "The contribution of biomass in the future global energy supply: a review of 17 studies," *Biomass and Bioenergy,* vol. 25 (2003), pp. 1–28. The following 13 studies were include in the analysis: WEC-World Energy Council, *New Renewable Energy Resources* (London: Kogan Page Ltd., 1994); IIASA-WEC-N. Nakicenovic et al., "Global energy perspectives" (Cambridge: International Institute for Applied Systems Analysis/ World Energy Council, 1998); FFES-M. Lazarus et al., "Towards a Fossil Free Energy Future" (Boston: Stockholm Environmental Institute, 1993); EDMONDS-J.A. Edmons et al., "Agriculture, land use, and commercila biomass energy: A preliminary integrated analysis of the potential role of biomass energy for reducing future greenhouse related emissions" (Pacific Northwest National Laboratory, 1996); SWISHER-J. Swisher and D. Wilson, "Renewable energy potentials," *Energy,* 18 (5), 1993, pp. 437- 459; USEPA-D.A. Lashof and D.A. Tirpak, (eds.), "Policy options for stabilizing global climate" (New York: Hemisphere Publishing Corprations, 1990); SORENSEN-B. Sorensen, "Long-term scenarios for global energy demand and supply: Four global greenhouse mitigation scenarios" (Roskilde: Roskilde University, Insitute 2, Energy & Environment Group, 1999); RIGES-T.B. Johannson et al., "A renewables-intensive global energy scenario (appendix to chapter 1)," in T.B. Johansson et al. (eds.), *Renewable Energy: Soiurces for Fuels and Electricity* (Washington, DC: Island Press, 1993), pp.1071–43; LESS/ BI-R.H. Willams, "Variants of a low CO2-emitting energy supply system (LESS) for the world," prepared for the IPCC Second Assessment Report Working Group Iia, Energy Supply Mitigation Options (Pacific Northwest Laboratories, 1995); LESS/ IMAGE-R. Leemans et al., "The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source," *Global Environmental Change*, 6 (4), 1996, pp. 335–57; BATTJES-J.J. Battjes, "Global options for biofuels from plantations acccording to IMAGE simulations" (Groningen, The Netherlands: Rijksuniversiteit Groningen, 1994); GLUE-H. Yamamoto et al., "Evaluation of bioenergy resources with a global land use and energy model formulated with SD technique," *Applied Energy*, 63, 1999, pp. 101-113; FISCHER-G. Fischer and L. Schrattenholyer, "Global bioenergy potentials through 2050," *Biomass and Bioenergy*, 20, 2000, pp. 151–59; DESSUS-B. Dessus et al., "World Potential of Renewable Energies: Actually Accessible in the Nineties and Environmental Impact Analysis" (Paris: 1992); SHELL-Shell International, "The evolution of the world's energy system 1860-2060" (London: Shell Center, 1995); SRES/ IMAGE-IPPC, *Special report on emission scenarios* (Cambridge: International Panel on Climate Change, 2000).
[4] Table 6–1 from Faaij, op. cit. note 2.
[5] Oak Ridge National Laboratory (ORNL), "Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply" (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy: February 2005), p. 15.
[6] Calliope Panoutsou, Center for Renewable Energy Sources, "Agricultural & Forestry Biomass in EU-25," presented at the 1st International Biorefinery Workshop (Washington, DC: 20–21 July 2005); ORNL, ibid.
[7] ORNL, op. cit. note 5, p. 15.
[8] Ibid., pp. 1–2.
[9] Frank Rosillo-Calle, "Biomass (Other Than Wood)," in World Energy Council, *Survey of Energy Resources 2001* (London: 2001)
[10] Wally Wilhelm, U.S. Department of Agriculture, Agricultural Research Service, "Sustainability of Crop Residues as Feedstock for Bio-based Products," presented at the 1st International Biorefinery Workshop, Washington, DC, 20–21 July 2005.

[11] Edward Smeets, Andre Faaij, and Iris Lewandowski, "A quickscan of global bioenergy potentials to 2050" (Utrecht: Copernicus Institute, Utrecht University: March 2004).). Updated results obtained from the authors, March 2006.
[12] D.O. Hall et al., "Biomass for Energy: Supply Prospects," in B.J. Johansson et al., eds., *Renewables for Fuels and Electricity* (Washington, DC: Island Press, 1993).
[13] Philippe Girard, Abigail Fallot, and Fabien Dauriac, "Biofuels Technology: State-of-the-Art," prepared for the Global Environment Facility (UNEP/GEF) Technical Workshop on Liquid Biofuels, New Delhi, India, 29 August–1 September 2005; Table 6–2 is based on International Sugar Organization, *ISO Sugar Yearbook 1999* (London: 1999); World Energy Council, "Biomass (Other Than Wood)," in *Survey of Energy Resources 2001* (London: 2001). The energy of a metric ton of bagasse is valued at 0.264 metric ton of coal equivalent; 1 ton of coal equivalent is 29.308 GJ, per United Nations, *Energy Statistics Yearbook* (New York: 1997).
[14] Smeets, Faaij, and Lewandowski, op. cit. note 11.
[15] Sidebar 6–1 from Jim Easterly, Easterly Consuting, personal communication with Peter Stair, Worldwatch Institute, March 2006.
[16] Rosillo-Calle, op. cit. note 9.
[17] Faaij, op. cit. note 2.
[18] Smeets, Faaij, and Lewandowski, op. cit. note 11.
[19] Andre Faaij, Copernicus Institute, Utrecht University, personal communication with Suzanne Hunt and Peter Stair, Worldwatch Institute, 3 March 2005.
[20] Smeets, Faaij, and Lewandowski, op. cit. note 11
[21] Ibid.
[22] Jose Roberto Moreira, "Global Biomass Energy Potential," prepared for the Expert Workshop on Greenhouse Gas Emissions and Abrupt Climate Change: Positive Options and Robust Policy (Paris: 2004), p. 2.
[23] Ibid.
[24] Smeets, Faaij, and Lewandowski, op. cit. note 11.
[25] Rosillo-Calle, op. cit. note 9.
[26] Faaij, op. cit. note 2.
[27] Ibid.
[28] Smeets, Faaij, and Lewandowski, op. cit. note 11.
[29] Ibid.
[30] Ibid.
[31] Faaij, op. cit. note 19.
[32] Bothwell Batidzirai et al., "Biomass and bioenergy supply from Mozambique," *Energy for Sustainable Development*, March 2006, p. 10.
[33] Table 6–3 Smeets, Faaij, and Lewandowski, op. cit. note 11.
[34] Ibid.
[35] Faaij, op. cit. note 19.
[36] Smeets, Faaij, and Lewandowski, op. cit. note 11; Faaij, op. cit. note 2.
[37] Andre Faaij et al., "Biomass potential assessment in Central and Eastern European countries and opportunities for the Ukraine" (Utrecht: Copernicus Institute, Utrecht University, January 2005).
[38] Smeets, Faaij, and Lewandowski, op. cit. note 11.
[39] Danielle Nierenberg, *Happier Meals: Rethinking the Global Meat Industry,* Worldwatch Paper 171 (Washington, DC: Worldwatch Institute, 2005).
[40] M. Hoogwijk et al., "Exploration of the ranges of the global potential of biomass for energy," *Biomass and Bioenergy*, vol. 25 no. 2 (2003), pp. 119–33.
[41] Smeets, Faaij, and Lewandowski, op. cit. note 11.
[42] Vaclav Smil, The Population and Development Review, vol. 28, no. 4 (2002), pp. 588-639.
[43] S. Peng et al., "Rice yields decline with higher night temperature from global warming," *Proceedings of the National Academy of Sciences*, 6 July 2004, pp. 9971–75.
[44] D.B. Lobell and G.P. Asner, "Climate and Management Contributions to Recent Trends in U.S. Agricultural Yields," *Science*, 14 February 2003, p. 1032.
[45] Faaij, op. cit. note 2.
[46] Figure 6–2 from Monique Hoogwijk, "On the global and regional potential of renewable energy sources" (Utrecht: Utrecht University, 2004).

[47] Ibid.
[48] Ibid.
[49] Faaij, op. cit. note 2.
[50] Ibid.
[51] Ibid.
[52] Ibid.
[53] Ibid.
[54] Ibid.
[55] Ibid.
[56] Ibid.
[57] Ibid.
[58] Ibid.
[59] Ibid.
[60] Ibid.
[61] V. Dornburg, and A. Faaij, "Cost and CO2 -Emission Reduction of Biomass Cascading: Methodological aspects and case study of SRF Poplar," *Climatic Change*, vol. 71, no. 3 (2005), pp. 373–408.

Chapter 7. Economic and Energy Security

[1] Suzanne C. Hunt and Janet L. Sawin, with Peter Stair, "Cultivating Renewable Alternatives to Oil," in Worldwatch Institute, *State of the World 2006* (Washington, DC: 2006).
[2] Figure 7–1 is based on the following sources**: 1**950–1993 from Worldwatch Institute database; 1993–2004 from BP, *Statistical Review of World Energy* (London: June 2005).
[3] Milton R. Copulos, "Economic, Security and Environmental Impacts of Alternative Fuel and Automotive Technologies. A Cost/Benefit Analysis of the Clean Cities Program" (Washington, DC: National Defense Council Foundation, 2005), p. 9.
[4] Jeff Rubin and Peter Buchanan, "The Global Crude Supply Outlook: Tighter Markets Ahead," CIBC World Markets Inc., *Monthly Indicators*, 9 January 2006.
[5] Figure 7–2 is based on the following sources: 1985–2004 from Platts, cited in BP, op. cit. note 2, p. 14; 2005 from U.S. Department of Energy (DOE), Energy Information Administration (EIA), *Short Term Energy Outlook* (Washington, DC: 7 February 2006).
[6] Noel Randewich, "Central American Poor Struggle as Oil Prices Rise," *Reuters*, 14 September 2005.
[7] Masami Kojima and Todd Johnson, "Potential for Biofuels for Transport in Developing Countries" (Washington, DC: World Bank, 2005); Tanzania Traditional Energy Development and Environment Organisation (TaTEDO), "Biofuels for Transportation in Tanzania Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Dar es Salaam: September 2005).
[8] W. Gehua et al., "Liquid Biofuels for Transportation: Chinese Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," report prepared for GTZ (Beijing: September 2005), p. 98.
[9] International Energy Agency (IEA), *World Energy Outlook 2004* (Paris: 2004).
[10] "What's up with oil prices," *Econbrowser,* 4 June 2005, at www.econbrowser.com/archives/2005/06/whats_up_with_o.html.
[11] RWE Aktiengesellschaft, "World Energy Report 2005: Determinants of Energy Prices" (Essen: 2005), p. 36.
[12] A. F. Alhajji, "The Failure of the Oil Weapon: Consumer Nationalism vs. Producer Symbolism" (Ada, OH: Ohio Northern Univeristy, 2005), available at www2.onu.edu/~aalhajji/ibec385/oil_weapon2.htm; M.S. Daoudi and M.S. Dajani, "The 1967 Oil Embargo Revisited" *Journal of Palestine Studies*, vol. 13, no. 2 (1984), pp. 65–90; Alan Dobson, "The Kennedy Administration and Economic Warfare against Communism," *International Affairs*, vol. 64, no. 2 (1988), pp. 599–616.
[13] "Oil: the flip side," *Associated Press*, 27 October 2004.
[14] James D. Hamilton, "Oil and the Macroeconomy Since World War II," *Journal of Political Economy*, vol. 91, no. 2 (1983), pp. 228–48.
[15] "Recycling the Petrodollars," *The Economist*, 12 November 2005.
[16] "In-depth: Economic diversification in Russia," World Economic Forum in Russia (Geneva: World Economic Forum, 18 November 2005), at www.weforum.org/site/homepublic.nsf/Content/Report+Russia+2005+-+theme+2.

[17] Commission of the European Communities (CEC), "Green Paper: A European Strategy for Sustainable, Competitive and Secure Energy" (Brussels: 8 March 2006), p. 16.
[18] German Federal Institute for Geosciences and Natural Resources (BGR), "Total known potential of conventional petroleum," www.bgr.bund.de/cln_030/nn_468074/EN/Home/homepage__node.html__nnn=true, viewed 28 April 2006.
[19] CEC, op. cit. note 17, p. 3.
[20] Jeffrey Rubin "The Time of Sands," CIBC World Markets Inc, *Monthly Indicators*, 9 January 2006.
[21] Michael Renner, *The Anatomy of Resource Wars*, Worldwatch Paper 162 (Washington, DC: Worldwatch Institute, 2002).
[22] K.Y. Amoako**,** Former Executive Secretary, Economic Commission for Africa, and Commissioner, Commission for Africa, presentation at Resources for Global Growth: Agriculture, Energy and Trade in the 21st Century conference, Washington, DC, 6 December 2005; Boris Utria, comments made at Biofuels Roundtable, Washington, DC, 7 July 2005.
[23] Ibid.
[24] The Energy and Resources Institute (TERI), "Biofuel for Transportation: India Country Study on Potential and Implications for Sustainable Agriculture and Energy," prepared for GTZ (New Delhi: October 2005), p. 46.
[25] IEA, "Analysis of the Impact of High Oil Prices on the Global Economy" (Paris: May 2004), p. 2; Merse Ejigu, "The Biofuels Option, The Way Ahead: Some Thoughts,' presentation at IEA Conference, Paris, 20–21 June 2005.
[26] Andre P.C. Faaij et al., "Mondiale beschikbaarheid en mogelijkheden voor import van biomassa voor energie in Nederland: Synthese van het onderzoeksproject GRAIN: Global Restrictions on Biomass Availability for Import to the Netherlands" (Utrecht: Vakgroep Natuurwetenschap & Samenleving, University of Utrecht, July 2000).
[27] Table 7–1 from Stephen Haley and Nydia R. Suarez, "Sugar and Sweeteners Outlook" (Washington, DC: U.S. Department of Agriculture, 2004), p. 37, at http://usda.mannlib.cornell.edu/reports/erssor/specialty/sss-bb/2004/sss241.pdf.
[28] Ejigu, op. cit. note 25.
[29]A. Faaij, A. Wierczorek, and M. Minnesma, "International Debate on International Biotrade," summary of international workshop, Amsterdam, The Netherlands, September 2002; Suani Teixeira Coelho, "Biofuels—Advantages and Trade Barriers" (Geneva: United Nations Conference on Trade and Development, 4 February 2005).
[30] Plinio Nastari, Isaias Macedo, and Alfred Szwarc, "Observations on the Draft Document Entitled 'Potential for Biofuels for Transport in Developing Countries'" (Brazil: October 2005), p.17.
[31] Glen S. Hodes, Boris E. Utria, and Anthony Williams, "Ethanol: Re-examining a Development Opportunity for Sub-Saharan Africa," draft for review (Washington, DC: The World Bank Group, September 2004).
[32] Ejigu, op. cit. note 25.
[33] Hunt et al., op. cit. note 1.
[34] Nastari, Macedo, and Szwarc, op. cit. note 30, p. 21.
[35] Isaias de Carvalho Macedo et al., "Sugar Cane's Energy: Twelve Studies on Brazilian Sugar Cane Agribusiness and Its Sustainability" (São Paulo: União da Agroindústria Canavieira de São Paulo, 2005), p. 195.
[36] TERI, op. cit. note 24.
[37] I.C. Macedo, R. Lima Verde Leal, and J. Silva, "Perspectivas de un Programa de Biocombustibles en América Central, Proyecto Uso Sustentable de Hidrocarburos, Comisión Económica para América latina y el Caribe" (Economic Commission for Latin America: 2004), at www.eclac.org.mx.
[38] Randewich, op. cit. note 6.
[39] Linda Hutchinson-Jafar, "Oil-Stung Caribbean Looks at Energy Alternatives," *Reuters*, 18 January 2006.
[40] Vanguard, "Nigeria's Search for an Alternative to Petrol," *Africa News*, 6 September 2005.
[41] Table 7–2 from U.S. General Accounting Office (GAO), "Petroleum and Ethanol Fuels: Tax Incentives and Related GAO Work," Letter to Senator Tom Harkin, 25 September 2000, at www.gao.gov/new.items/rc00301r.pdf.

[42] Masami Kojima and Todd Johnson, “Potential for Biofuels for Transport in Developing Countries” (Washington, DC: World Bank, 2005), p. 71.
[43] Milton R. Copulas, “America's Achilles Heel—The Hidden Costs of Imported Oil” (Washington, DC: National Defense Council Foundation, October 2003).
[44] J. Moore et al., “Oil Imports: An Overview and Update of Economic and Security Effects,” CRS Report for Congress 98-1 (Washington, DC: 12 December 1997).
[45] Kojima and Johnson, op. cit. note 42.
[46] U.S. Department of Agriculture (USDA), Farm Service Agency, “FY 2005 Production of Bioenergy Program Participants and Payments Earned by Commodity” (Kansas City, MO: 12 December 2005), at www.fsa.usda.gov/daco/bioenergy/2005/FY2005ProductPayments.pdf.
[47] Carol Werner, “Subsidies: Historic, Current and the Skewing of Market Signals,” Environmental and Energy Study Institute, presentation to conference, Policy, Institutions and the True Costs of Carbon Albuquerque, NM, 29 July 2005, at www.eesi.org/publications/Presentations/NCC%20Energy%20Subsidies%207.29.05.pdf, viewed 7 March 2006.
[48] Kojima and Johnson, op. cit. note 42, p. 28.
[49] Renewable Fuels Association, Ethanol Facts: Economy” and “Ethanol Trade Fact Sheet,” fact sheets (Washington, DC: 2005), at www.ethanolrfa.org/resource/facts.
[50] DOE, EIA, *Annual Energy Outlook 2006* (Washington, DC: February 2006).
[51] L.R. Lynd et al., “Bioenergy: Background, Potential, and Policy” (Washington, DC: Center for Strategic and International Studies, 2003).
[52] Kojima and Johnson, op. cit. note 42, p. 91.
[53] Public Citizen, “Down on the Farm: NAFTA’s Seven-Years War on Farmers and Ranchers in the U.S., Canada and Mexico” (Washington, DC: 2001).
[54] “Soaring sugar prices unsettle Brazilian ethanol market*,” F.O. Licht’s World Ethanol and Biofuels Report*, 7 February 2006; “Rapeseed prices continue to climb on EU biodiesel demand,” *F.O. Licht’s World Ethanol and Biofuels Report*, 14 February 2006; Barani Krishnan and Sambit Mohanty, “Commodities - Bullish Palm Looks to Biofuel for Future,” *Reuters*, 23 February 2006
[55] Organisation for Economic Co-operation and Development (OECD), “Agricultural Market Impacts of Future Growth in the Production of Biofuels” (Paris: Working Party on Agricultural Policies and Markets, February 2006), p. 31.
[56] Ibid., p. 27.
[57] A. Regmi et al., “Changing Structure of Global Food Consumption and Trade” (Washington, DC: USDA Economic Research Service, 2001).
[58] Coelho, op. cit. note 29.
[59] Centre for International Economics, “Impact of ethanol policies on feedgrain users in Australia,” report prepared for MLA on behalf of the Australian Beef Industry (Canberra and Sydney: August 2005).
[60] Ibid.
[61] TERI, op. cit. note 24.
[62] New Uses Council, Environmental and Energy Studies Institute, and North Carolina Solar Center, “Development of a Workable Incentives System for Biobased Products, Biofuels and Biopower,” project description, September 2005, p. 3.
[63] Kojima and Johnson, op. cit. note 42.
[64] GAO, op. cit. note 41.
[65] DOE, Federal Energy Management Program, “Biomass and Alternative Methane Fuel Super ESPCs Helping Federal Facilities Turn Waste into Energy,” *FEMP Focus*, November 2002.
[66] Council for Biotechnology Information, “Answers to frequently asked questions about biotech biofuels,” at www.whybiotech.com/index.asp?id=5035, viewed 25 December 2005.
[67] Lynd et al., op. cit. note 51.
[68] Emily A. Heaton et al., “Miscanthus for Renewable Energy Generation: European Union Experience and Projections for Illinois” (Champaign, IL: University of Illinois at Urban-Champaign, October 2003), p. 13.
[69] Vinod Khosla, “Biofuels: Think Outside the Barrel,” presentation to Center for American Progress, 10 January 2006, at www.khoslaventures.com/presentations/Biofuels_Dec2005.v3.2.ppt.
[70] IEA, op. cit. note 25.
[71] TERI, op. cit. note 24, p. 46.

[72] Danielle Murray, "Rising Oil Prices Will Impact Food Supplies," peopleandplanet.net, 13 September 2005.
[73] Ibid.
[74] Steven Heckeroth, "Toward Sustainable Agriculture" (Albion, CA: 1999), at www.renewables.com/Permaculture/SustAgri.htm, viewed 25 December 2005.
[75] OECD, op. cit. note 55, p. 27.
[76]Ann Bordetsky et al., "Securing America: Solving our Oil Dependence through Innovation" (New York: Natural Resources Defense Council and Institute for the Analysis of Global Security, 2005).
[77] Copulos, op. cit. note 43.
[78] Keith Bradsher, *High and Mighty*: *The Dangerous Rise of the SUV* (New York: PublicAffairs, 2002); Brett Clanton, "Large SUVs lose luster, cost big 3," *The Detroit News,* 18 January 2005.
[79] Ed Garsten, "High gas prices scare of the sales of SUV's: Automakers depend on big vehicle sales for pumping up the bottom line," *The Detroit News*, 15 March 2005.
[80] United Auto Workers, "The American Auto Industry in Crisis: The threat to middle-class jobs, wages, health care, and pensions," *United Auto Workers News and Views,* 8 December 2005; Sholnn Freeman and Amy Joyce, **"**Ford to Cut 14 Plants and Up to 30,000 Jobs—N. American Auto Division Lost $1.6 Billion in 2005," *Washington Post*, 24 January 2006.
[81] "Toyota Licenses Hybrid Technology to Ford," autoweb.com, 25 March 2004, at http://autoweb.drive.com.au/cms/A_101177/newsarticle.html.
[82] Choren Industries Web site, at www.choren.de.
[83] Iogen Corporation Web site, at www.iogen.ca.

Chapter 8. Implications for Agriculture and Rural Development

[1] Michael Duffy, Associate Professor of Economics, Iowa State University, "The Changing Structure of Agriculture," presented at Independent Insurance Agents of Iowa Rural Agents Conference (Ames, Iowa: 26 January 2006)
[2] Bill Kovarik, "Henry Ford, Charles Kettering and the 'Fuel of the Future,'" *Automotive History Review*, Spring 1998, pp. 7–27, available at www.radford.edu/~wkovarik/papers/fuel.html.
[3] Ethanol share of corn crop from "USDA raises corn use estimate for fuel ethanol production," *F.O. Licht's World Ethanol and Biofuels Report,* 8 March 2006; U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, "Biofuels and the Economy," at http://permanent.access.gpo.gov/websites/www.ott.doe.gov/biofuels/economics.html; Renewable Fuels Association (RFA), "Homegrown for the Homeland: Ethanol Industry Outlook 2005" (Washington, DC January 2005), at www.ethanolrfa.org/objects/pdf/outlook/outlook_2005.pdf.
[4] Kevin C. Dhuyvetter, Terry L. Kastens, and Michael Boland, "The U.S. Ethanol Industry: Where will it be located in the future?" newsletter (Davis, CA: University of California, Agricultural Issues Center, November 2005), p. i; Food and Agricultural Policy Research Institute (FAPRI), "Implications of Increased Ethanol Production for U.S. Agriculture" (Columbia, MO: University of Missouri-Columbia, August 2005).
[5] Lori Wilcox, "Energy Outlook: Impacts on Biofuels and Implications for the Farm Sector," presentation at 2005 Crop Management Conference, Fapri, Missouri, 14 December 2005, available at www.fapri.missouri.edu/outreach/presentations/2005/cropmang_dec05.pdf.
[6] Candida Jones, "Europe Adopts Biodiesel: Can an African Bean Crack Europe's Biodiesel Blockage?" *EcoWorld*, 28 September 2005
[7] "EU Rapeoil Selling Out for Biofuel Use," *Oil World*, 19 October 2005.
[8] Isaias de Carvalho Macedo et al., "Sugar Cane's Energy: Twelve Studies on Brazilian Sugar Cane Agribusiness and Its Sustainability" (Sao Paulo: União da Agroindústria Canavieira de São Paulo, 2005).
[9] "Soaring Sugar Prices Unsettle Ethanol Market," *F.O. Licht's World Ethanol and Biofuels Report*, 20 February 2006.
[10] "North coast sugar industry to benefit from biofuels decision," *ABC News Online,* 29 November 2005; "Australia's Queensland Sees Ethanol Sector As Sugar Saviour," *F.O. Licht's World Ethanol and Biofuels Report*, 26 September 2005.
[11] "Grape biofuel may lift the spirits of French vinters," *Reuters*, 16 November 2005; Jones, op. cit. note 6.
[12] Peter Apps, "South Africa Maize Farmers See Ethanol Plant In 18 Months," *Reuters*, 15 March 2005,
[13] Anna Mudeva, "Interview- Malaysia IOI Eyes Green Energy Expansion in Europe," *Reuters*, 23 November 2005

[14] "Biofuels to Ease Economic Pain," *F.O. Licht's World Ethanol and Biofuels Report*, 1 December 2005; "Sugar Exports May Hit New Low," *F.O. Licht's World Ethanol and Biofuels Report*, 7 October 2005.
[15] Perfecto G. Corpuz, "Philippines Oilseeds and Products. GRP Promotes Biodiesel Use 2004," *GAIN Report* (Washington, DC: U.S. Department of Agriculture (USDA) Foreign Agricultural Service, 3 May 2004); five million from "Biodiesel plant seen to help coco industry," *Sun Star Magazine*, 9 June 2005; "The rest of the world," *F.O. Licht's World Ethanol and Biofuels Report*, 9 November 2005; "Ethanol bill to become law before year-end," *The Manila Times*, 15 October 2005.
[16] "Biofuel Use Spreads Vegoil Supplies Too Thin for Margarine Firms, Says Imace," *F.O. Licht's World Ethanol and Biofuels Report*, 9 November 2005.
[17] Centre for International Economics, "Impact of Ethanol Policies on Feedgrain Users in Australia," prepared for MLA on behalf of the Australian Beef Industry (Canberra and Sydney: August 2005).
[18] "Ethanol to Have Mixed Impact on US Agriculture," *F.O. Licht's World Ethanol and Biofuels Report*, 9 November 2005.
[19] Jones, op. cit. note 6; D1 Oils, "D1 Oils biodiesel land reclamation project launched in the Philippines," press release (London: 5 May 2005).
[20] Marie Walsh et al., "Biomass Feedstock Availability in the United States: 1999 State Level Analysis" (Oak Ridge, TN: Oak Ridge National Laboratory, updated January 2000).
[21] Potential to increase farmer income from Jim Hettenhaus, "Talking about corn stover with Jim Hettenhaus," in *The Carbohydrate Economy* (Minneapolis, MN: Institute for Local Self-Reliance, Summer 2002).
[22] Daniel G. De La Torre Ugarte et al., "The Economic Impacts of Bioenergy Crop Production on U.S. Agriculture," Agricultural Economic Report Number 815 (Washington, DC: USDA, February 2003).
[23] "A look at the EU's proposed sugar reforms," International Policy Council for Food and Agricultural Trade (Washington, DC: 2005), at www.agritrade.org/Publications/EU%20Sugar %20Reform.pdf.
[24] European Commission (EC), "An EU Strategy for Biofuels," Communication from the Commision (Brussels, 7 February 2006).
[25] Macedo et al., op. cit. note 8.
[26] Walsh et al., op. cit. note 20.
[27] Ibid.
[28] DOE, op. cit. note 3; RFA, op. cit. note 3; U.S. National Renewable Energy Laboratory, "Biomass for Sustainable Transportation" (Golden, CO: 2000), at www.nrel.gov/docs/fy00osti/25876.pdf.
[29] Wuppertal Institute for Climate, Environment, and Energy, "Synopsis of German and European Experience and State of the Art of Biofuels for Transport," prepared for Deutsche Gesellschaft Für Technische Zusammernarbeit (GTZ) GmbH (Wuppertal: 2005), p. 40.
[30] Sivan Kartha, Gerald Leach, and Sudhir Chella Rajan, "Advancing Bioenergy for Sustainable Development. Guideline for Policymakers and Investors. Volumes I, II, and III" (Washington, DC: World Bank Energy Sector Management Assistance Program, April 2005), p. 11.
[31] Wuppertal Institute for Climate, Environment, and Energy, op. cit. note 29, p. 40.
[32] Suani Teixeira Coelho, "Biofuels—Advantages and Trade Barriers" (Geneva: United Nations Conference on Trade and Development, 4 February 2005).
[33] Sybille de La Hamaide, "French to Boost Biofuel Output to Meet EU Target," *Reuters*, 14 June 2005.
[34] J. Domac, K. M. Richards, and V. Segon, "Old fuel for modern times. Socio-economic drivers and impacts of bioenergy use" (Paris: International Energy Agency Bioenergy Task 29, 2005), p. 8, at www.iea-bioenergytask29.hr/pdf/Domac_Richards_Segon_2005.pdf.
[35] "Domestic Fuel Ethanol Program Proposed," *F.O. Licht's World Ethanol and Biofuels Report*, 25 July 2005.
[36] W. Gehua et al., "Liquid Biofuels for Transportation: Chinese Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," report prepared for GTZ (Beijing: September 2005), p. 94.
[37] Masami Kojima and Todd Johnson, "Potential for Biofuels for Transport in Developing Countries" (Washington, DC: World Bank: October 2005).
[38] Ibid.
[39] Ibid., p. 129.
[40] USDA, Economic Research Service, "Rural population and migration: rural population change and net migration," at www.ers.usda.gov/briefing/population/popchange, viewed 6 March 2006; Michael Duffy, Associate Professor of Economics, Iowa State University, "The Changing Structure of Agriculture,"

presentation at Independent Insurance Agents of Iowa Rural Agents Conference, Ames, IA, 26 January 2006.
[41] Kartha, Leach, and Rajan, op. cit. note 30, p. 11; Kojima and Johnson, op. cit. note 37.
[42] FAPRI, op. cit. note 4, p. 1; Michael Duffy, Associate Professor of Economics, Iowa State University, "Where is the Profit?" presentation at Southeast Research and Demonstration Farm Annual Meeting, Ames, IA, 4 March 2004.
[43] Figure 8–1 from Franz J. Kaltner et al., "Liquid Biofuels for Transportation in Brazil: Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for GTZ (Rio de Janeiro: 2005), p. 88 and from Jones, op. cit. note 6.
[44] The Energy and Resources Institute, "Biofuel for Transportation: India Country Study on Potential and Implications for Sustainable Agriculture and Energy," prepared for GTZ (New Delhi: October 2005), p. 44.
[45] Ibid., pp. 44–45.
[46] Kaltner et al., op. cit. note 43.
[47] Luiz Prado, Director of Brazil Programs, LaGuardia Foundation, e-mail to Suzanne Hunt, Worldwatch Institute, 28 January 2006.
[48] "Brazil poised to become biodiesel giant," www.int.iol.co.za (South Africa), 19 November 2005.
[49] "Brazil embraces alternative energy," *Environment News Service*, 19 August 2005.
[50] Kaltner et al., op. cit. note 43.
[51] "World's first tallow-biodiesel plant in Brazil," *MercoPress*, 27 October 2005.
[52] Prado, op. cit. note 47.
[53] Daniel G. De La Torre Ugarte et al., op. cit. note 22.
[54] Kevin Watkins and Joachim von Braun, "Time to Stop Dumping on the World's Poor," *2002-2003 IFPRI Annual Report* (Washington, DC: International Food Policy Research Institute, 2003).
[55]Bruce Gardner, "Fuel Ethanol Subsidies and Farm Price Support: Boon or Boondoggle? " (College Park, MD: University of Maryland Department of Agricultural and Resource Economics, October 2003).
[56] "Data Shows Ethanol Will Pass Exports as #2 Corn Use by 2008," *High Plains Journal*, 9 June 2005; Wilcox, op. cit. note 5.
[57] RFA, op. cit. note 3; John Urbanchuk and Jeff Kapell, "Ethanol and the Local Community" (Mt. Laurel, NJ and Boston: AUS Consultants and SJH & Company, 20 June 2002); David Morris, "The Ethanol Glass Is Still Only Half Full," *Ethanol Today*, September 2003.
[58] Nancy Novak, "The Rise of Ethanol in Rural America," *Ag Decision Maker* (Iowa State University), June 2002.
[59] De La Torre Ugarte et al., op. cit. note 22**.**
[60] Kojima and Johnson, op. cit. note 37, p. 131.
[61] Macedo et al., op. cit. note 8, pp. 51–64.
[62] Glen S. Hodes, Boris E. Utria, and Anthony Williams, "Ethanol: Re-examining a Development Opportunity for Sub-Saharan Africa," draft for review (Washington, DC: World Bank, September 2004).
[63] Energetics and NEOS Corporation, "Economic Impact of Ethanol Production Facilities: Four Case Studies," prepared for Western Regional Biomass Energy Program and Great Lakes Regional Biomass Energy Program (Golden, CO and Chicago: June 1994)
[64] National Corn Growers Association, "Taking Ownership of Grain Belt Agriculture," at www.ncga.com/public_policy/takingOwnership/index.htm, viewed 6 March 2006
[65] Jones, op. cit. note 6.
[66] "Interview: Farmers are 'tomorrow's sheiks" due biofuels," *Reuters*, 10 November 2005.
[67] Prado, op. cit. note 47.
[68] Neil Lyon, "Taxation of on-farm biodiesel favouring fossil fuels," *The Land* (New South Wales, Australia), 13 October 2005.
[69] Kojima and Johnson, op. cit. note 37.
[70] Rogerio Carneiro de Miranda, Winrock International, e-mail to Peter Stair, Worldwatch Institute, 16 February 2006.
[71] Mali and Sidebar 8–1 from Ibrahim Togola, Mali Folkecenter, Bamako, Mali, visit to Worldwatch Institute, Washington, DC, 26 July 2005.
[72] Ibid.
[73] Ibid.; Merse Ejigu, "Assessing the Biofuels Option, The Way Ahead: Some Thoughts," presentation to International Energy Agency conference, Paris, 20–21 June 2005.

[74] Tanzania Traditional Energy Development and Environment Organisation (TaTEDO), “Biofuels for Transportation in Tanzania Potential and Implications for Sustainable Agriculture and Energy in the 21st Century,” prepared for GTZ (Dar es Salaam: September 2005).
[75] Macedo et al., op. cit. note 8.
[76] David Morris, Institute for Local Self-Reliance, Minneapolis, MN, “Ownership Matters: Three Steps to Ensure a Biofuels Industry That Truly Benefits Rural America,” presentation at the Minnesota Ag Expo 2006, Morton, MN, 25 January 2006.
[77] Brian Halweil, “Where Have All the Farmers Gone?,” *World Watch*, September/October 2000, p. 17.
[78] Corn flakes from Halweil, ibid.; Duffy, op. cit. note 42.
[79] Halweil, op. cit. note 77.
[80] Watkins and von Braun, op. cit. note 54.
[81] Macedo et al., op. cit. note 8, p. 203.
[82] Minnesota Department of Agriculture, “The Minnesota Ethanol Program,” at www.mda.state.mn.us/ethanol/about.htm#ngcnote, viewed 6 March 2006; John M. Urbanchuk,” The Contribution of the Ethanol Industry to the American Economy in 2004” (Wayne, PA: 12 March 2004), at www.ncga.com/ethanol/pdfs/EthanolEconomicContributionREV.pdf.
[83] Kurt Klein et al., “Ethanol Policies, Programs and Production in Canada,” PowerPoint Presentation, Center for Research in the Economics of Agrifood, Laval University, Ste. Foy, Quebec, Canada, at www.farmfoundation.org/projects/documents/klein-ethanol.ppt, viewed 6 March 2006.
[84] Stephen Thompson, “Biodiesel with attitude: Colorado’s Blue Sun Biodiesel grows rapeseed for biodiesel production,” *Rural Cooperatives* (USDA), November/December 2004.
[85] Blue Sun Biodiesel, “News and Events,” at www.gobluesun.com, viewed 6 March 2006.
[86] Bart Minten, Lalaina Randrianarison, and Johan F.M. Swinnen. “Global Retail Chains and Poor Farmers: Evidence from Madagascar,” September 2005, p. 1.
[87] William Burnquist, Centro de Tecnologia Canavieira, Piracicaba, Brazil, conversation with Suzanne Hunt and Peter Stair, Worldwatch Institute, 24 October 2005.
[88] Prado, op. cit. note 47.
[89] Kaltner et al., op. cit. note 43, p. 36.
[90] Gehua et al., op. cit. note 36; Wu Yong, “Liaoning adopts ethanol gasoline,” *China Daily,* 1 November 2005.
[91] Morris, op. cit. note 76.
[92] RFA, “Plant Locations,” at www.ethanolrfa.org/industry/locations, viewed 3 April 2006.
[93] The New Rules Project, “Ethanol Production—The Minnesota Model,” at www.newrules.org/agri/ethanol.html, viewed 3 April 2006; Dhuyvetter, Kastens, and Boland, op. cit. note 4.
[94] Joel Severinghaus, “Why we import Brazilian ethanol,” trade report (West Des Moines, IA: Iowa Farm Bureau Federation, 14 July 2005).
[95] Joe Mead, Sales Associate, World Energy Alternatives, conversation with Peter Stair, Worldwatch Institute, 20 August 2005.
[96] ADM Plans to Expand Ethanol Capacity by 500 Million Gallons,” *PR Newswire*, 4 October, 2005
[97] “EU Approves French-Dutch Biodiesel JV,” *F.O. Licht’s World Ethanol and Biofuels Report*, 7 October 2005.
[98] Kaltner et al., op. cit. note 43, p. 36.
[99] Stephanie Simon, “To replace oil, U.S. experts see amber waves of plastic,” *Los Angeles Times*, 28 June 2005.
[100] International Fund for Agricultural Development, “IFAD Strategic Framework for 2002-2006” (Rome: March 2002).
[101] Kojima and Johnson, op. cit. note 37; biodiesel from Prado, op. cit. note 47.
[102] Amartya Sen, “Why Half the Planet Is Hungry,” *Observer of London*, 16 June 2002.

Chapter 9. International Trade in Biofuels

[1] M. Hoogwijk et al., “Exploration of the ranges of the global potential of biomass for energy,” *Biomass and Bioenergy*, vol. 25 no. 2 (2003), pp. 119–33.
[2] Suzanne C. Hunt and Janet L. Sawin, with Peter Stair, “Cultivating Renewable Alternatives to Oil,” in Worldwatch Institute, *State of the World 2006* (Washington, DC: 2006).

[3] Ibid.
[4] Brazil from Patrick Knight, "New Flex-Fuel Engines Transform Consumer Options in Brazil," *F.O. Licht's World Ethanol and Biofuels Report*, 23 July 2003; Table 9–1 from Jim Jordan and Associates, "Ethanol: Prospectus: World Markets for Fuel Ethanol" (Houston, TX: September 2005).
[5] Christoph Berg, "World Ethanol Analysis and Outlook," *F.O. Licht's World Ethanol and Biofuels Report,* April 2004.
[6] Masami Kojima and Todd Johnson, "Potential for Biofuels for Transport in Developing Countries" (Washington, DC: World Bank, October 2005), p. 97; "Brazil's Petrobras to Sell Ethanol in Japan," *Kyodo News*, 20 December 2005.
[7] "Petrobras Forms Ethanol Joint Venture in Japan," *Green Car Congress,* 19 December 2005, at www.greencarcongress.com/2005/12/petrobras_forms.html.
[8] Jane Earley, Thomas Earley, and Matthew Straub, "Specific Environmental Effects of Trade Liberalization: Oilseeds" (Washington, DC: International Policy Council for Food and Agriculture, October 2005), pp. 10–14.
[9] Mark Ash and Erik Dohlman, "Soybeans and Oil Crops: Trade" (Washington, DC: U.S. Department of Agriculture (USDA), Economic Research Service, April 2005).
[10] "Energy Oil and Palm," *The Rams Horn: Journal of Food Systems Analysis,* January 2006.
[11] "Malaysia to Build Three Biodiesel Plants Fueled by Palm Oil," *Agence France-Presse*, 28 September 2005; John Burton, "Malaysia Likely to Legislate Biofuel Use," *Financial Times*, 7 October 2005.
[12] "EarthFirst Importing Biodiesel to US; Soy Lobby Reacts," *Green Car Congress,* 14 November 2006, at www.greencarcongress.com.
[13] Center for Science in the Public Interest, "Cruel Oil: How Palm Oil Impacts Health, Rainforest and Wildlife" (Washington, DC: May 2005).
[14] European Commission (EC), "An EU Strategy for Biofuels" (Brussels: 7 February 2006), pp. 24–26.
[15] Ibid, p. 6.
[16] Figure 9–1 from Lew Fulton et al., *Biofuels for Transport* (Paris, France: International Energy Agency (IEA), 2004), p. 185.
[17] Ibid.
[18] EC, op. cit. note 14, pp. 24–26.
[19] Brent D. Yacobucci, "Ethanol Imports and the Caribbean Basin Initiative" (Washington, DC: Energy Policy Resources, Science, and Industry Division, Congressional Research Service, September 2004), at http://ncseonline.org/NLE/CRSreports/04Sep/RS21930.pdf.
[20] Ash and Dohlman, op. cit. note 9.
[21] HART Downstream Energy Services, "Ethanol Market Fundamentals," report to The New York Board of Trade (New York: 9 March 2004); Suani Teixeira Coelho, "Biofuels-Advantages and Trade Barriers" (Geneva: United Nations Conference on Trade and Development, 4 February 2005).
[22] Institute for Agriculture and Trade Policy (IATP), Trade and Governance Program, "CAFTA's Impact on U.S. Ethanol Market" (Minneapolis: June 2005), p. 3.
[23] HART Downstream Energy Services, op. cit. note 21.
[24] IATP, op. cit. note 22.
[25] Hunt and Sawin, with Stair, op. cit. note 3.
[26] Karin Bendz, "EU-25 Agricultural Situation Pakistan, EU's second largest ethanol exporter, loses privileged status," *GAIN Report* (Washington, DC: USDA, Foreign Agricultural Service (FAS), 27 September 2005).
[27] Karin Bendz, "EU-25 Oilseeds and Products Annual. 2005," *GAIN Report* (Washington, DC: USDA, FAS, 10 June 2005).
[28] Table 9–2 from EC, "EU Biomass Action Plan" (Brussels: 7 December 2005), p. 34.
[29] Bendz, op. cit. note 26.
[30] EC, op. cit. note 28, p. 34.
[31] Karin Bendz, "EU-25 Oilseeds and Products, Biofuels situation in the European Union, 2005," *GAIN Report* (Washington, DC: USDA, FAS, 23 March 2005); Wuppertal Institute for Climate, Environment, Energy, "Synopsis of German and European experience and state of the art of biofuels for transport," prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Wuppertal: July 2005), p. 15.

[32] "Fast–Tracking a 'Feasible' EU-Mercosur Agreement: Scenarios for Untying the Agricultural Knot," draft prepared for the Working Group on EU-Mercosur Negotiations of the Mercosur Chair of Sciences Po, Paris, presented at a workshop at the Faculty of Law, Barcelona, Spain, 29 March 2004.
[33] Environmental Working Group, "Top Subsidies in the US 1995-2004," Farm Subsidy Database, at www.ewg.org/farm/region.php?fips=00000, viewed 27 January 2006; Alexei Barrionuevo, "A Warning About Trade Suits Over Agriculture," *New York Times,* 30 November 2005.
[34] Oxfam International, "The EU Sugar Scam: How Europe's sugar regime is devastating livelihoods in the developing world," Oxfam Briefing Paper 27 (Oxford, UK: 2002).
[35] Earley, Earley and Straub, op. cit. note 8, p. 4.
[36] Martin von Lampe, "Agricultural Market Impacts of Future Growth in the Production of Biofuels" (Paris: Organisation for Economic Co-operation and Development, 2006), p. 25.
[37] U.S. Senator Ken Salazar, "Report on the 2006 Colorado Renewable Energy Summit" (Denver: 16 Februrary 2006), at http://salazar.senate.gov/images/pdf/SummitReport060216.pdf.
[38] David Borough, "The Future of Ethanol in Europe Hinges on State Aid," *Reuters*, 6 December 2005.
[39] "Living and Dying on History and Artificial Economic Sweeteners," *The Economist*, 24 September 2005.
[40] International Centre for Trade and Sustainable Development (ICTSD), "EU Releases Reform Plan for Sugar," *Bridges Weekly Trade Digest*, 29 June 2005.
[41] EC, "Sugar reform will offer EU producers long-term competitive future," press release (Brussels: 22 June 2005); EC, "EU radically reforms its sugar sector to give producers long-term competitive future," press release (Brussels: 24 November 2005).
[42] Daryll E. Ray, Daniel G. De La Torre Ugarte, and Kelly J. Tiller, "Rethinking US Agricultural Policy: Changing Course to Secure Farmer Livelihoods Worldwide" (Nashville: Agricultural Policy Analysis Center The University of Tennessee, 2003).
[43] World Trade Organization Web site, at www.wto.org
[44] David Waskow, International Progam Director, Friends of the Earth-US, personal communication with Lauren Sorkin and Suzanne Hunt, Worldwatch Institute, 17 February 2006.
[45] ICTSD, "WTO Environment Committee Drafts Text for Hong Kong," *Bridges Weekly Trade Digest,* 16 November 2005.
[46] Daniel De La Torre Ugarte, "The Contribution of Bioenergy to a New Energy Paradigm" (Knoxville, TN: Agricultural Policy Analysis Center, University of Tennessee, 2005), p. 1.
[47] The Energy and Resources Institute (TERI), "Seminar on trade liberalization in Environmental Goods and Services" (New Delhi: 16 May 2003); Iris Lewanski and Andre Faaij, "Steps Toward the Development of a Certification System for Sustainable Bio-energy Trade" (Utrecht: Copernicus Institute of Sustainable Development and Innovation), July 2004.
[48] Robert Howse, "Post-Hearing Submission to the International Trade Commission: World Trade Law and Renewable Energy: The Case of Non-Tariff Measures" (Vienna: Renewable Energy and International Law Project, 5 May 2005), p. 16.
[49] Coelho, op. cit. note 21; Wuppertal Institute for Climate, Environment, Energy, op. cit. note 31, p. 46.
[50] TERI, "Biofuel for Transportation: India Country Study on Potential and Implications for Sustainable Agriculture and Energy" (New Delhi: GTZ, October 2005), p. 48; ICTSD, "Can London Deliver What Hong Kong Couldn't?" *Bridges Weekly Trade Digest,* January-February 2006.
[51] The New York Board of Trade Web site, at www.nybot.com.
[52] **"**Ethanol Starting to Trade Like a World Commodity," *Reuters*, 29 September 2005.
[53] EC, op. cit. note 14, p. 9.
[54] Paul Anthony A. Isla, "RP, Thailand agree on regional biofuel standard," *The Manila Times*, 1 September 2004.
[55] Jason Clay, Vice President, Center for Conservation Innovation, World Wildlife Fund, presentation at Resources for Global Growth: Agriculture, Energy and Trade in the 21st Century conference, Washington, DC, 6 December 2005.
[56] EC, op. cit. note 14.
[57] "Germany Sets Quotas for Biofuel in Fuel from 2007," *Reuters*, 3 May 2006.
[58] Radhika Singh, "Literature Review on Biodiesel," The University of the South Pacific, written for The South Pacific Applied Geoscience Commission (Suva, Fiji: undated).
[59] Table 9–3 based on the following sources: Isla, op. cit. note 55; South Africa from D1 Oils Plc., "South Africa—Biodiesel is a National Priority," at www.d1plc.com/global/africa_south_africa.php, viewed 3 March 2006.

[60] National Biodiesel Board, “Guidance Issued 30 November 2005” (Jefferson City, MO: 30 November 2005), available at www.biodiesel.org/pdf_files/Biodiesel_Blends_Above%20_20_Final.pdf.
[61] National Biodiesel Board, “Fuel Fact Sheets: Standards and Warranties,” www.biodiesel.org/resources/fuelfactsheets/standards_and_warranties.shtm, viewed 2 March 2006.
[62] Isla, op. cit. note 55.
[63] Singh, op. cit. note 59.
[64] Dennis Olson, Director, Trade and Agriculture Project, IATP, e-mail to Lauren Sorkin, Worldwatch Institute, 27 February 2006.

Chapter 10. Energy Balances of Current and Future Biofuels

[1] Table 10-1 is based on the following sources: D. Lorenz and D. Morris, “How Much Energy Does It Take to Make a Gallon of Ethanol?” (Washington, DC: Institute for Local Self Reliance, August 1995); U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, “Net Energy Balance for Bioethanol Production and Use,” at www1.eere.energy.gov/biomass/net_energy_balance.html, updated 8 February 2006; M. Wang, “The Debate on Energy and Greenhouse Gas Emissions Impacts of Fuel Ethanol,” presentation to Energy Systems Division Seminar, Argonne National Laboratory, Chicago, IL, 3 August 2005, at www.transportation.anl.gov/pdfs/TA/347.pdf; M.A. Elsayed, R. Matthews, and N.D. Mortimer, “Carbon and Energy Balances for a Range of Biofuels Options,” report prepared for the British DTI Sustainable Energy Programmes (Sheffield, UK: Sheffield Hallam University, March 2003), p. 20; G. Azevedo, Director, GilTech Consultants for Technology and Sustainable Development, Brazil, e-mail to Peter Stair, Worldwatch Institute, 22 November 2005; Franz Kaltner, presentation cited in Azevedo, op. cit. this note; W. Gehua et al., “Liquid Biofuels for Transportation: Chinese Potential and Implications for Sustainable Agriculture and Energy in the 21st Century,” report prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Beijing: September 2005); Isaias de Carvalho Macedo et al., “Sugar Cane’s Energy: Twelve Studies on Brazilian Sugar Cane Agribusiness and Its Sustainability” (São Paulo: União da Agroindústria Canavieira de São Paulo, 2005), p. 60; J. Sheehan et al., “Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in An Urban Bus” (Golden, CO: National Renewable Energy Laboratory, May 1998); I.R. Richards, “Energy balances in the growth of oilseed rape for biodiesel and of wheat for bioethanol,” report prepared for the British Association for Bio Fuels and Oils (BABFO) (Levington Park Ipswich, Suffolk, UK: Levington Agriculture Ltd., June 2000), at www.biodiesel.co.uk/levington.htm; BABFO, “Rationale and Economics of a British Biodiesel Industry (London: 1994), at www.biodiesel.org/resources/reportsdatabase/reports/gen/19940401_gen-294.pdf; Agence de l’Environnment et de la Maîtrise de l’Energie (ADEME) and Direction des Ressources Energétiques et Minérales (DIREM), “Energy and Greenhouse Gas Balances of Biofuels’ Production Chains in France” (Paris: Ecobilan/PricewaterhouseCoopers, December 2002), at www.ademe.fr/partenaires/agrice/publications/documents_anglais/synthesis_energy_and_greenhouse_english.pdf; Hosein Shapouri et al, “Energy Balance/Life Cycle Inventory for Ethanol, Biodiesel and Petroleum Fuels” (Washington, DC: U.S. Department of Agriculture (USDA), July 2005); NTB Liquid Biofuels Network, “NTB Liquid Biofuels Network - The European Network for removing non-technical barriers to the development of liquid biofuels,” at www.biomatnet.org/secure/Ec/S1016.htm; Marco Aurélio dos Santos, “Energy Analysis of Crops Use for Producing Ethanol and CO_2 Emissions” (Rio de Janeiro: Energy Planning Program, COPPE/UFRJ, Cidade Universitária, undated), at www.ivig.coppe.ufrj.br/doc/alcofoen.pdf.
[2] Lew Fulton et al., *Biofuels For Transport: An International Perspective* (Paris: International Energy Agency, April 2004), pp. 51–64.
[3] Hosein Shapouri, Senior Economist, USDA, Washington, DC, e-mail to Peter Stair, Worldwatch Institute, 10 January 2006.
[4] Robert Brown, Office of Biorenewables Program, Iowa State University, “A Question of Balance,” e-mail to Peter Stair, Worldwatch Institute, 30 November 2005.
[5] Sheehan et al., “Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in An Urban Bus,” op. cit. note 1.
[6] Brown, op. cit. note 4.
[7] R. Larsen et al., “Might Canadian Oil Sands Promote Hydrogen Production for Transportation? Greenhouse Gas Emission Implications of Oil Sands Recovery and Upgrading.” paper submitted to World

Resource Review (Chicago: Center for Transportation Research, Argonne National Laboratory, December 2004), p. 12.

[8] J. Sheehan et al., "Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol," *Journal of Industrial Ecology*, vol. 7, no. 3–4 (2004).

[9] Richards, op. cit. note 1; ADEME/DIRIM, op. cit. note 1.

[10] Fulton et al., op. cit. note 2, p. 58

[11] U.S. from Hosein Shapouri, "The 2001 Net Energy Balance of Corn-Ethanol" (Washington, DC: USDA, 2004); Brazil from Macedo et al., op. cit. note 1, p. 101.

[12] "The Potential of *Jatropha curcas* in Rural Development and Environment Protection – An Exploration," concept paper for a workshop sponsored by the Rockefeller Foundation and Scientific & Industrial Research & Development Centre, Harare, Zimbabwe, 13–15 May 1998, available at www.jatropha.de/zimbabwe/rf-conf1.htm.

[13] Jacob Bugge, "Note: Rape Seed Oil for Transport 1: Energy Balance and CO_2 Balance" (Hurup Thy, Denmark: Folkecenter for Renewable Energy, 11 September 2000), at www.folkecenter.dk/plant-oil/publications/energy_co2_balance.pdf.

[14] ADEME/DIRIM, op. cit. note 1; Richards, op. cit. note 1.

[15] ADEME/DIRIM, op. cit. note 1. Sheehan et al., op. cit. note 1; Richards, op. cit. note 1.

[16] Ibid.

[17] Wang, op. cit. note 1.

[18] Shapouri, op. cit. note 3.

[19] Ibid.

[20] Ibid.; production of fertilizer from Richards, op. cit. note 1.

[21] Wang, op. cit. note 1; Macedo et al., op. cit. note 1.

[22] Novozymes & BBI International, "Fuel Ethanol: A Technological Evolution" (Bagsvaerd, Denmark: June 2005, at www.bbibiofuels.com/ethanolevolution.

[23] Shapouri, op. cit. note 3.

[24] Robert Anex, Associate Professor of Agricultural Systems and Bioengineering, Iowa State University, personal communication with Peter Stair, Worldwatch Institute, 15 August 2005

[25] Brown, op. cit. note 4.

[26] Macedo et al., op. cit. note 1.

[27] Novozymes & BBI International, op. cit. note 22.

[28] Chippewa Valley Ethanol Company and Frontline Bioenergy LLC, "CVEC Announces Alliance with Frontline BioEnergy, LLC," press release (Ames, IA and Benson, MN: 12 December 2005).

[29] Macedo et al., op. cit. note 1.

[30] Brown, op. cit. note 4.

[31] DOE, Office of Energy Efficiency and Renewable Energy, "Roadmap for Agricultural Biomass Feedstock Supply in the United States" (Washington, DC: November 2003).

[32] Anex, op. cit. note 24.

Chapter 11. Effects on Greenhouse Gas Emissions and Climate Stability

[1] Earth has warmed by 0.6° Celsius over the past 30 years and by 0.8° C over the past 100 years, per U.S. National Aeronautics and Space Administration, "2005 Warmest Year in Over a Century," news feature (Washington DC: 24 January 2006), at www.nasa.gov/vision/earth/environment/2005_warmest.html.

[2] Kevin A. Baumert, Timothy Herzog, and Jonathan Pershing, "Navigating the Numbers: GHG Data and Climate Policy" (Washington, DC: World Resources Institute, 2005); Intergovernmental Panel on Climate Change, Working Group III, *IPCC Third Assessment Report, Climate Change 2001: Mitigation* (Cambridge University Press: 2001).

[3] Share of global emissions in Lew Fulton et al., *Biofuels for Transport: An International Perspective* (Paris: International Energy Agency (IEA), 2004), p. 174; share of U.S. emissions in Nathanael Greene et al., *Growing Energy: How Biofuels Can Help End America's Oil Dependence* (Washington, DC: Natural Resources Defense Council, December 2004), pp. iv, 8; share of European emissions in European Commission (EC), Directorate-General for Energy and Transport, "Promoting Biofuels in Europe: Securing a Cleaner Future for Transport" (Brussels: 2004), p. 6.

[4] "Key GHG data—GHG Emission Data for 1990-2003," United Nations Framework Convention on Climate Change (2005), p. 69, cited in EC, "Commission Staff Working Document, Annex to the Communication from the Commission: An EU Strategy for Biofuels, Impact Assessment" (Brussels: 2006), p. 4.
[5] Analysis by the European Environment Agency Topic Centre on Air Emissions and Climate Change (EEA-ETC/ACC) cited in Peter Taylor, "Transport Emission Trends in Europe," presentation at "The Biofuels Directive: Potential for Climate Protection?" European Climate Forum, 3rd Autumn Conference, Tyndall Centre, University of East Anglia, Norwich, UK, 8–10 September 2003.
[6] Masami Kojima and Todd Johnson, "Potential for Biofuels for Transport in Developing Countries" (Washington, DC: World Bank, 2005), p. 17.
[7] Assumptions about the relative efficiency of gasoline versus biofuel (or blended fuel) vehicles can result in up to 10 percent variation in a study's final results, per Lew Fulton et al., *Biofuels for Transport* (Paris: International Energy Agency, 2004), p. 54.
[8] Energy balance from M. Wang, C. Saricks, and D. Santini, "Effects of Fuel Ethanol on Fuel-Cycle Energy and Greenhouse Gas Emissions" (Argonne, IL: Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, January 1999); co-products from Fulton et al., op. cit. note 4, p. 52.
[9] Markus Quirin et al., "CO_2 Mitigation through Biofuels in the Transport Sector: Status and Perspectives, Main Report" (Heidelberg: Institute for Energy and Environmental Research, August 2004), p. 12.
[10] IEA, Bioenergy Task 38, "Standard Methodology for calculation of GHG balances" (Paris: 2006).
[11] Quirin et al., op. cit. note 9.
[12] See, for example, Fulton et al., op. cit. note 4, pp. 52–66; Quirin et al., op. cit. note 9; Eric D. Larson, "Liquid Biofuel Systems for the Transport Sector: A Background Paper," draft for discussion at the Global Environment Facility Scientific and Technical Advisory Panel Workshop on Liquid Biofuels, New Delhi, 29 August–1 September 2005; Alexander E. Farrell et al., "Ethanol Can Contribute to Energy and Environmental Goals," *Science*, 27 January 2006, pp. 27–29.
[13] Same vehicle efficiency from Fulton et al., op. cit. note 4, p. 64.
[14] Ibid., p. 54.
[15] André Faaij, Associate Professor and Coordinator Research Energy Supply & System Studies, Copernicus Institute, Utrecht University, the Netherlands, e-mail to Suzanne Hunt, Worldwatch Institute, 3 March 2006.
[16] Nitrous oxide from Larson, op. cit. note 12, p. 14.
[17] D.S. Powlson, A.B. Riche, and I. Shield, "Biofuels and Other Approaches for Decreasing Fossil Fuel Emissions from Agriculture," *Annals of Applied Biology*, vol. 146 (2005), pp. 193–201.
[18] Robert Edwards, "Updated WTW Analysis of Biomass-Based Transport Fuels," PowerPoint presentation, Joint Research Centre, European Commission, Paris, 2005, slide 32; A.P. Armstrong et al., "Energy and Greenhouse Gas Balance of Biofuels for Europe—an Update," CONCAWE Report No. 2/02 (Brussels: April 2002), p. 13.
[19] IEA, "Greenhouse Gas Balances of Bioenergy Systems" (Paris: IEA Bioenergy Task 25, 1998).
[20] Jason Clay, *World Agriculture and Environment* (Washington, DC: Island Press, 2004), p. 219.
[21] Franz J. Kaltner et al., "Liquid Biofuels for Transportation in Brazil: Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Rio de Janeiro: Fundação Brasileira para o Desenvolvimento Sustentável, 2005), p. 50.
[22] Larry Rohter, " A Record Amazon Drought, and Fear of Wider Ills," *New York Times*, 11 December 2005; "Brazil's New National Park Protects Vanishing Savannah," *Environment News Service*, 15 December 2005.
[23] Jim Cook and Jan Beyea, "An Analysis of Environmental Impacts of Energy Crops in the USA: Methodologies, Conclusions and Recommendations" (Washington, DC: National Audubon Society, undated), available at www.panix.com/~jimcook/data/ec-workshop.html, viewed 18 July 2005; Larson, op. cit. note 12, p. 15.
[24] Ibid.
[25] Powlson, Riche, and Shield, op. cit. note 17.
[26] Ibid.
[27] Larson, op. cit. note 12, p. 15.

[28] Melvin Cannell, "Carbon Sequestration," presentation at "The Biofuels Directive: Potential for Climate Protection?" European Climate Forum, 3rd Autumn Conference, Tyndall Centre, University of East Anglia, Norwich, UK, 8–10 September 2003.
[29] Powlson, Riche, and Shield, op. cit. note 17.
[30] Ibid.
[31] United Nations Environment Programme (UNEP), *Global Environment Outlook, GEO-2000* (Nairobi 2000).
[32] Quirin et al., op. cit. note 9, p. 19.
[33] John Sheehan et al., "Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol," *Journal of Industrial Ecology*, vol. 7, no. 3–4 (2004), p. 138.
[34] Powlson, Riche, and Shield, op. cit. note 17.
[35] "Researchers Explore Climate-Friendly Farming," GreenBiz.com, 27 June 2005.
[36] Christoph Berg, "World Fuel Ethanol Analysis and Outlook," *F.O. Licht's World Ethanol and Biofuels Report*, April 2004.
[37] Sakamoto Yakuhin Kogyo, Ltd., "Glyerol," at www.sy-kogyo.co.jp/English/sei/1_gly.html, viewed 22 May 2005.
[38] Journey to Forever, "Vegetable Oil Yields," at www.journeytoforever.org/biodiesel_yield.html, viewed 16 May 2005.
[39] Oak Ridge National Laboratory (ORNL), "Biofuels from Switchgrass: Greener Energy Pastures," brochure (Oak Ridge, TN: undated), at http://bioenergy.ornl.gov/papers/misc/switgrs.html.
[40] "Hybrid Grass May Prove to be Valuable Fuel Source," *Science Daily*, 9 September 2005; ORNL, "Popular Poplars: Trees for Many Purposes" (Oak Ridge, TN: undated), at http://bioenergy.ornl.gov/misc/poplars.html, viewed 10 March 2006.
[41] Carl Trettin, Aletta Davis, and John Parsons, "Sustainability of High-Intensity Forest Management with Respect to Water and Soil Quality and Site Nutrient Reserves," prepared by U.S. Forest Service, Southern Research Station and North Carolina State University (Oak Ridge, TN: U.S. Department of Energy (DOE), Office of Biomass, Oak Ridge National Laboratory, August 2003); switchgrass carbon sequestration in Greene et al., op. cit. note 4, p. v; low pesticides from S. McLaughlin et al., "Developing Switchgrass as a Bioenergy Crop," in J. Janick, ed., *Perspectives on New Crops and New Uses* (Alexandria, VA: ASHS Press, 1999), pp. 282–99; carbon and tilling from Powlson, Riche, and Shield, op. cit. note 17.
[42] Higher yield in Martin Tampier et al., "Identifying Environmentally Preferable Uses for Biomass Resources, State 2 Report: Life-Cycle GHG Emissions Reduction Benefits of Selected Feedstock-to-Product Threads," prepared for Natural Resources Canada and National Research Council Canada (North Vancouver, BC: Envirochem Services Inc., 19 July 2004), p. 113; root system from Greene et al., op. cit. note 4, p. 31.
[43] W.W. Wilhelm and J. Cushman, "Implications of Using Corn Stalks as a Biofuel Source: A Joint ARS and DOE Project," *Eos. Trans. Ag,,* vol. 84, no. 46 (2003), available at ars.usda.gov/research/publications/publications.htm?SEQ_NO_115=166979.
[44] U.S. Department of Agriculture (USDA), Soil Quality Institute (SQI), "Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations," White Paper (Washington, DC: 4 March 2003), pp. 2-6.
[45] Ibid.
[46] Greene et al., op. cit. note 4, pp. v, 29.
[47] USDA, SQI, op. cit. note 44.
[48] S. Park et al., "Identifying On-farm Management Practices Aimed at Reducing Greenhouse Gas Emissions from Sugarcane Primary Production," in *Proceedings of the 11th Australian Agronomy Conference, 2–6 February 2003* (Geelong, Victoria: Australian Society of Agronomy, 2004).
[49] Fulton et al., op. cit. note 4, p. 52.
[50] Ibid., p. 53.
[51] Kojima and Johnson, op. cit. note 7, p. 24.
[52] See for example, B. J. Somera and K. K. Wu, "Energy Inventory of Hawaiian Sugar Plantations—1995," Energy Report 35 (Alea, HI: Hawaii Agriculture Research Center, August 1996).
[53] M.A. Delucchi, "A Model of Lifecycle Energy Use and Greenhouse-gas Emissions of Transportation Fuels and Electricity," cited in IEA, op. cit. note 19.

[54] M. A. Delucchi, "Conceptual and methodological issues in lifecycle analyses of transportation fuels," (Davis, CA: University of California at Davis, 2004), cited in Farrell et al., op. cit. note 12.
[55] Armstrong et al., op. cit. note 18, p. 10.
[56] S. Kim and B.E. Dale, **"**Allocation Procedure in Ethanol Production System from Corn Grain," *International Journal of Life Cycle Assessment*, vol. 7 (2002), p. 237, cited in Farrell et al., op. cit. note 12.
[57] Fulton et al., op. cit. note 4, p. 52.
[58] Armstrong et al., op. cit. note 18, p. v.
[59] John Sheehan et al., "Life Cycle Inventory of Biodiesel and Petroleum Diesel" (Golden, CO: National Renewable Energy Laboratory (NREL), May 1998), p. 117; A. Aden et al., "Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover" (Golden, CO: NREL, June 2002), p. 9.
[60] Wuppertal Institute for Climate, Environment, Energy, "Synopsis of German and European Experience and State of the Art of Biofuels for Transport," prepared for GTZ (Wuppertal: July 2005), pp. 28–29.
[61] Sheehan et al., op. cit. note 59, pp. 48, 50.
[62] Fulton et al., op. cit. note 4, p. 66.
[63] Carlo N. Hamelinck, Roald A.A. Suurs, and André P.C. Faaij, "International Bioenergy Transport Costs and Energy Balance," *Biomass and Bioenergy*, vol. 29, no. 2 (2005), pp. 114–34.
[64] André Faaij, Associate Professor and Coordinator Research Energy Supply & System Studies, Copernicus Institute, Utrecht University, the Netherlands, e-mail to Suzanne Hunt, Worldwatch Institute, 10 March 2006.
[65] Sheehan et al., op. cit. note 59, p. 221.
[66] Quirin et al., op. cit. note 9.
[67] Larson, op. cit. note 12, p. 11.
[68] Farrell et al., op. cit. note 12.
[69] Quirin et al., op. cit. note 9, p. 44.
[70] Larson, op. cit. note 12, p. 2.
[71] Fulton et al., op. cit. note 4, p. 52; Quirin et al., op. cit. note 9, pp. 15–18.
[72] Quirin et al., op. cit. note 9, pp. 15–18.
[73] Larson, op. cit. note 12, p. 2.
[74] David Pimentel, "Ethanol Fuels: Energy Security, Economics, and the Environment," *Journal of Agricultural and Environmental Ethics*, vol. 4 (1991); and David Pimentel, "The Limits of Biomass Energy," *Encyclopaedia of Physical Sciences and Technology*, September 2001, both cited in Fulton et al., op. cit. note 4, p. 53.
[75] David Pimentel, "Ethanol Fuels: Energy Balance, Economics and Environmental Impacts are Negative," *Natural Resources Research*, vol. 12, no. 2 (2003), pp. 127–134; D. Pimentel and T. Patzek, *Natural Resources Research*, vol. 14, no. 65 (2005); T. Patzek, "Thermodynamics of the Corn-Ethanol Biofuel Cycle," *Critical Reviews in Plant Sci*ences, vol. 23, no. 519 (2004).
[76] Farrell et al., op. cit. note 12, pp. 27–29; Quirin et al., op. cit. note 9, p. 8.
[77] For example, Mark A. Delucchi, "A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials. Documentation of Methods and Data" (Davis, CA: Institute of Transportation Studies (ITS), University of California at Davis, December 2003); M. A. Delucchi, "Conceptual and methodological issues in lifecycle analyses of transportation fuels," (Davis, CA: ITS, University of California at Davis, 2004); and Mark A. Delucchi, "A Multi-Country Analysis of Lifecycle Emissions from Transportation Fuels and Motor Vehicles" (Davis, CA: ITS, University of California at Davis, May 2005).
[78] Mark A. Delucchi, Research Scientist, ITS, University of California at Davis, e-mail to Janet Sawin, Worldwatch Institute, 10 March 2006; Delucchi, "A Multi-Country Analysis of Lifecycle Emissions from Transportation Fuels and Motor Vehicles," ibid., p. 44.
[79] Delucchi, op. cit. note 78; Delucchi, "A Lifecycle Emissions Model…," op. cit. note 77.
[80] M.A. Elsayed, R. Matthews, and N.D. Mortimer, "Carbon and Energy Balances for a Range of Biofuels Options," prepared for UK Department of Trade and Industry Sustainable Energy Programmes (London: March 2003), p. 23; Fulton et al., op. cit. note 4; Kojima and Johnson, op. cit. note 7, pp. 88–89.
[81] Table 11–1 is based on the following sources: Kojima and Johnson, op. cit. note 7, p. 89: Fulton et al., op. cit. note 4, pp. 53, 59; Farrell et al., op. cit. note 12; Wuppertal Institute, op. cit. note 60, p. 29; G. Wang et al., "Liquid Biofuels for Transportation: Chinese Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for GTZ (Beijing: Tsinghua University, November

2005), p. 84; Armstrong et al., op. cit. note 18; Tom Beer et al., “Comparison of Transport Fuels,” final report submitted to the Australia Greenhouse Office on Stage 2 Study of Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles (Clayton South, Victoria: Commonwealth Scientific and Industrial Research Organisation: 2002), at www.greenhouse.gov.au/transport/comparison; Delucchi, “A Multi-Country Analysis…,” op. cit. note 77, p. 100; Isaias de Carvalho Macedo, Manoel Regis Lima Verde Lea, and Joao Eduardo Azevedo Ramos da Silva, “Assessment of Greenhouse Gas Emissions in the Production and Use of Fuel Ethanol in Brazil” (São Paulo: April 2004), at www.unica.com.br/i_pages/files/pfd-ingles.pdf; Wang, Saricks, and Santini, op. cit. note 8; EC, “Application of biologically derived products as fuels or additives in combustion engines” (Brussels: Directorate-General XII Science, Research and Development: 1994); R.H. Levy, “Les biocarburants. Report to the French Government based on figures from the Commission Consultative pour la Production des Carburants de Substitution” (Paris: 1993); G. Marland and A.F. Turhollow, “CO_2 emissions from the production and combustion of fuel ethanol from corn,” *Energy*, vol. 16, no. 11/12, pp. 1307–16; GM et al., ”GM Well-to Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicles Systems – A European Study; ANNEX – Full Background Report” (Ottobrunn, Germany, 2002), at www.lbst.de/gm-wtw; M.P. Gover et al., “Alternative Road Transport Fuels—A Preliminary Life-Cycle Study for the UK,” ETSU Report R92 Volumes 1 & 2 (Oxford: Energy Technology Support Unit, 1996); Levelton Engineering Ltd., “Engineering Assessment of Net Emissions of Greenhouse Gases from Ethanol –Gasoline Blends in Southern Ontario” (Richmond, BC: January 2000), at www.tc.gc.ca/programs/Environment/climatechange/docs/ETOH-FNL-RPTAug30-1999.htm; Michael Wang, “Greet Model version 1.5a”, revision June 2001 (calculations made by IEA for reference case using the downloadable model, in consultation with author), http://greet.anl.gov.

[82] Wang, Saricks, and Santini, op. cit. note 8, pp. 1–3.

[83] Farrell et al., op. cit. note 12.

[84] Larson, op. cit. note 12, pp. 2-3.

[85] Delucchi, op. cit. note 78.

[86] Kojima and Johnson, op. cit. note 7, pp. 88–89.

[87] Kaltner et al., op. cit. note 21, p. 84.

[88] Fulton et al., op. cit. note 4, pp. 59–60.

[89] Edwards, op. cit. note 18, slide 25; Quirin et al., op. cit. note 9, p. 20.

[90] Table 11–2 is based on the following sources: Kojima and Johnson, op. cit. note 7, pp. 89, 221; Wuppertal Institute, op. cit. note 81; Jean-François Larivé, “The Joint JRC/EUCAR/CONCAWE Well-to-Wheels Study,” PowerPoint presentation, 4th CONCAWE Symposium, 30 November–1 December 2005, slide 14; Armstrong et al., op. cit. note 18; Beer et al., op. cit. note 81; Delucchi, “A Multi-Country Analysis…,” op. cit. note 77; Gover et al., op. cit. note 81; GM et al., op. cit. note 81; Levelton Engineering Ltd., op. cit. note 81; K. Scharmer and G. Gosse, “Energy balance, ecological impact and economics of vegetable oil methylester production in Europe as a substitute for fossil diesel,” report commissioned by GET Germany and INRA France (Brussels: EU ALTENER Programme, 1996); I.R. Richards, “Energy balances in the growth of oilseed rape for biodiesel and of wheat for bioethanol,” report for the British Association of Bio Fuels and Oils (BABFO) (Ipswich: Levington Agriculture Ltd., 2000); Netherlands Agency for Energy and Environment (NOVEM), ”Conventional Bio-Transporation Fuels. An Update,” Report 2GAVE-03.10 (Utrecht: May 2003), www.ecn.nl/_files/bio/Report_2GAVE-03.10.pdf; John Sheehan et al., “An Overview of Biodiesel and Petroleum Diesel Life Cycles” (Golden, CO: NREL, May 1998).

[91] Delucchi, “A Lifecycle Emissions Model…,” op. cit. note 77.

[92] Delucchi, op. cit. note 78.

[93] Larson, op. cit. note 12, pp. 2–3.

[94] Ibid., pp. 17–18.

[95] Quirin et al. op. cit. note 9, p. 20.

[96] Fulton et al., op. cit. note 4, p. 51.

[97] Wuppertal Institute, op. cit note 60, p. 26.

[98] Clay, op. cit. note 20, pp. 176–177, 211, 412; Wang, Saricks, and Santini, op. cit. note 8, p. 11; continued development in Fulton et al., op. cit. note 4, pp. 65–66; National Biodiesel Board, “Biodiesel as a Greenhouse Gas Reduction Option,” (Jefferson City, MO: undated), at www.biodiesel.org/resources/reportsdatabase/reports/gen/20040321_gen-332.pdf; Wang et al., op. cit. note 8.

[99] Clay, op. cit. note 20, pp. 176–177, 211, 412; Wang, Saricks, and Santini, op. cit. note 8, p. 11.
[100] Fulton et al., op. cit. note 4, p. 136; K.P. Vogel and R.A. Masters, "Developing Switchgrass into a Biomass Fuel Crop for the Midwestern USA," paper presented at BioEnergy '98: Expanding Bioenergy Partnerships, Madison, WI, 4–8 October 1998; breeding from Powlson, Riche, and Shield, op. cit. note 17.
[101] Kojima and Johnson, op. cit. note 7, p. 57.
[102] Fulton et al., op. cit. note 4, pp. 60–61.
[103] Plinio Mário Nastari, "Ethanol: The Global Overview," presentation at International Ethanol Conference, Brisbane, Australia, 9–10 May 2005, available at www.sdi.qld.gov.au/dsdweb/v3/documents/objdirctrled/nonsecure/pdf/11584.pdf.
[104] Angelo Bressan Filho, Director, AgroEnergy Program, Brazilian Ministry of Environment, "The AgriEnergy Option for the Future," presentation at the Workshop and Business Forum on Sustainable Biomass Production for the World Market, São Paulo, Brazil, 30 November–2 December 2005.
[105] Dutch Energy Agency (NOVEM) and Arthur D. Little (ADL), *Analysis and Evaluation of GAVE Chains*, Vol. 1–3 (Utrecht: GAVE Analysis Programme, December 1999).
[106] Quirin et al., op. cit. note 9, p. 39.
[107] Tampier et al., op. cit. note 42, p. 102.
[108] Wang, Saricks, and Santini, op. cit. note 8, p. 15.
[109] Tampier et al., op. cit. note 42, p. 13.
[110] P. Börjesson and G. Berndes, "Multi-functional Biomass Production Systems"(Lund, Sweden; Lund University, undated).
[111] Quirin et al., op. cit. note 9.
[112] Table 11–3 is based on the following sources: Beer et al., op. cit. note 81; Delucchi, "A Multi-Country Analysis…," op. cit. note 77, p. 100; GM et al., op. cit. note 81; Wang, op. cit. note 81; Levelton Engineering Ltd., op. cit. note 81.
[113] Larson, op. cit. note 12, pp. 17–18.
[114] Fulton et al. op. cit. note 4, pp. 61–62.
[115] Delucchi, op. cit. note 78; Mark A. Delucchi, Research Scientist, ITS, University of California at Davis, e-mail to Janet Sawin, Worldwatch Institute, 13 March 2006.
[116] Fulton et al. op. cit. note 4., pp. 61–62.
[117] Ibid.
[118] Wang, Saricks, and Santini, op. cit. note 8, p. 3.
[119] Table 11–4 from NOVEM and ADL, op. cit. note 105.
[120] Genencor International, "Transforming the Ethanol Industry," backgrounder (Palo Alto, CA: June 2005).
[121] Thomas F. Riesing, "Cultivating Algae for Liquid Fuel Production," *The Permaculture Activist*, no. 59, March 2006, pp. 48–50.
[122] M. Kerssen and R.H. Berends, "Life Cycle Analysis of the HTU Process" (Apeldoom, The Netherlands: Dutch Research Organization for Environment, Energy and Process Innovation, 2005), available at www.novem.nl/default.asp?menuld=10&documentId=115819.
[123] Brad Lemley, "Anything into Oil," *Discover*, May 2003.
[124] Fulton et al., op. cit. note 4, p. 65.
[125] Figure 11–1 from Lew Fulton, Sustainable Transport, Division of Global Environment Facility Coordination, United Nations Environment Programme, e-mail to Peter Stair, Worldwatch Institute, July 2005.
[126] Andre Faaij, "Modern Biomass Conversion Technologies," *Mitigation and Adaptation Strategies for Global Change*, draft accepted for publication, 2005.
[127] Larson, op. cit. note 12, pp. 17–18.
[128] Data and Figure 11–2 from Fulton et al., op. cit. note 4, pp. 91–94.
[129] Suzanne Hunt and Janet Sawin, with Peter Stair, "Cultivating Renewable Alternatives to Oil," in Worldwatch Institute, *State of the World 2006* (New York: W.W. Norton & Company, 2006), p. 64.
[130] Kojima and Johnson, op. cit. note 7, pp. 41, 105.
[131] Jane Michael Henke, Gernot Klepper, and Norbert Schmitz, "Tax Exemption for Biofuels in Germany: Is Bio-Ethanol Really an Option for Climate Policy?" Kiel Working Paper No. 1184 (Kiel: Kiel Institute for World Economics, September 2003), cited in ibid., p. 90; abatement cost from EC, op. cit. note 5, p. 14.
[132] Larivé, op. cit. note 11, slide 18.

[133] Kojima and Johnson, op. cit. note 7, p. 90.
[134] Low end of range is for conventional production, increased derogation; high end is for conventional production, current derogation. N.D. Mortimer et al., "Evaluation of the Comparative Energy, Global Warming and Socio-Economic Costs and Benefits of Biodiesel," report prepared for the UK Department for Environment, Food and Rural Affairs, Report no. 20/1 (London: January 2003), p. ix.
[135] Ibid.
[136] Fulton et al., op. cit. note 4, pp. 93–94; Carlo N. Hamelinck and André Faaij, "Outlook for Advanced Biofuels," *Energy Policy*, 2005**.**
[137] Carlo N. Hamelinck, "Outlook for Advanced Biofuels," doctoral dissertation (Utrecht: Utrecht University, June 2004), pp. 41–42; and Faaij, op. cit. note 64.
[138] Hamelinck and Faaij, op. cit. note 136.
[139] Ibid.
[140] Fulton et al., op. cit. note 4, pp. 93–94; little room for cost improvements also from Hamelinck and Faaij, op. cit. note 136.
[141] Tony Dammer, Office of Naval Petroleum and Oil Shale Reserves, U.S. Department of Energy, "Strategic Significance of America's Oil Shale Resource," presentation at 2005 Energy Information Agency Midterm Energy Outlook Conference, Washington, DC, 12 April 2005, available at www.eia.doe.gov/oiaf/archive/aeo05/conf/pdf/dammer.pdf.
[142] Sierra Club of Canada, "Mackenzie Pipeline to Fuel America's Gas Tank," press release (Ottawa: 14 April 2004); Nature Canada, "How Tempting is the Mackenzie Gas Project for Canada's North?" *Nature Canada*, Summer 2004.
[143] For example, see M.A. Elsayed et al., op. cit. note 80, p. 23 and Kojima and Johnson, op. cit. note 7, pp. 41, 90.
[144] Armstrong et al., op. cit. note 18, cited in Kojima and Johnson, op. cit. note 7, p. 90.
[145] R.L. Graham, L.L. Wright, and A.F. Turhollow, "The Potential for Short-Rotation Woody Crops to Reduce U.S. CO_2 Emissions," *Climatic Change*, vol. 22 (1992), pp. 223–238, cited in Robin L. Graham, Wei Liu and Burton C. English, "The Environmental Benefits of Cellulosic Energy Crops at a Landscape Scale," from *Environmental Enhancement through Agriculture: Proceedings of a Conference*, Tufts University, Boston, MA, 15-17 November 1995.
[146] Faaij, op. cit. note 126.
[147] Tampier et al., op. cit. note 42, p. 103.
[148] IEA, op. cit. note 19.
[149] B. Schlamadinger and G. Marland, "Some Results from the Graz/Oak Ridge Carbon Accounting Model (GORCAM), cited in IEA, op. cit. note 19.
[150] Veronika Dornburg and André P.C. Faaij, "Cost and CO_2-Emission Reduction of Biomass Cascading: Methodological Aspects and Case Study of SRF Poplar," *Climatic Change*, August 2005, pp. 373–408.
[151] Tampier et al., op. cit. note 42, p. 103.
[152] Faaij, op. cit. note 64.
[153] Larson, op. cit. note 12, p. 2.

Chapter 12. Environmental Impacts of Feedstock Production

[1] J.S. Dukes, "Burning Buried Sunshine: Human Consumption of Ancient Solar Energy," *Climatic Change*, vol. 6, no. 1-2 (2003), pp. 31–44, available at http://globalecology.stanford.edu/DGE/Dukes/Dukes_ClimChange1.pdf; A. Lovins et al., *Winning the Oil Endgame* (Snowmass, CO: Rocky Mountain Institute, 2005), p. 2.
[2] Society of Petroleum Engineers (SPE), "Seismic Technology," at www.spe.org/spe/jsp/basic/0,,1104_1714_1004089,00.html, viewed June 2005.
[3] M. Mann and P. Spath, "Life Cycle Assessment of a Biomass Gasification Combined-Cycle Gasification System" (Golden, CO: National Renewable Energy Laboratory (NREL), December 1997), pp. 43–44.
[4] Ibid, p. 48.
[5] U.S. Geological Survey. "Subsidence and Fault Activation Related to Fluid Energy Production, Gulf Coast Basin Project" (Washington, DC: Coastal and Marine Geology Program 21 March 2005), at http://coastal.er.usgs.gov/gc-subsidence/overview.html.
[6] Mann and Spath, op. cit. note 3, p. 57.
[7] Ibid, p. 58.

[8] S. Gerrard et al., "Drill Cuttings Piles in the North Sea: Management Options During Platform Decommissioning," Research Report 31 (Norwich, UK: Centre for Environmental Risk, University of East Anglia, 1999).
[9] SPE, "How is the Industry Working to Protect the Environment?", at www.spe.org/spe/jsp/basic/0,,1104_1008218_1109940,00.html, viewed June 2005; SPE, "Seismic Technology," op. cit. note 2.
[10] W. Baue, **"**ChevronTexaco Faces Class-Action Lawsuit in Ecuador Over Environmental Damage," SocialFunds.com, 11 May 2004, at www.socialfunds.com/news/article.cgi/article1419.html.
[11] World Petroleum Council, "Exploration and Production in the Marine Environment," at www.world-petroleum.org/education/exprod/, viewed June 2005.
[12] Tony Dammer, Office of Naval Petroleum and Oil Shale Reserves, U.S. Department of Energy, "Strategic Significance of America's Oil Shale Resource," presentation at 2005 Energy Information Administration Midterm Energy Outlook Conference, Washington, DC, 12 April 2005, available at www.eia.doe.gov/oiaf/archive/aeo05/conf/pdf/dammer.pdf.
[13] Robert Collier, "Fueling America: Oil's Dirty Future—Canadian Oil Sands: Vast Reserves Second to Saudi Arabia Will Keep America Moving, But at a Steep Environmental Cost," *San Francisco Gate*, 22 May 2005.
[14] Colorado Environmental Coalition et al., "Oil Shale and Tar Sands Resources Leasing Programmatic EIS; Scoping Comments," comments submitted to the U.S. Bureau of Land Management and Argonne National Laboratory, 31 January 2006, pp. 18–43.
[15] Franz J. Kaltner et al., "Liquid Biofuels for Transportation in Brazil: Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared by Fundação Brasileira para o Desenvolvimento Sustentável for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Rio de Janeiro: 2005), p. 50.
[16] Jason Clay, *World Agriculture and Environment* (Washington, DC: Island Press, 2004), p. 165.
[17] Plinio Nastari, Isaias Macedo, and Alfred Szwarc, "Observations on the Draft Document Entitled 'Potential for Biofuels for Transport in Developing Countries" report prepared for the World Bank Air Quality Thematic Group (Brazil: 2005), pp. 56–57.
[18] Suani Teixeira Coelho, "Biofuels—Advantages and Trade Barriers," presentation at the United Nations Conference on Trade and Development, Geneva, 4 February 2005, p. 14.
[19] More than one-fourth from "Brazil's New National Park Protects Vanishing Savannah," *Environment News Service*, 15 December 2005; sugarcane expansion from Manoel Regis Lima Verde Leal, Pesquisador Associado, e-mail to Peter Stair, Worldwatch Institute, 2 December 2005.
[20] Kaltner et al., op. cit. note 15, p. 50.
[21] Ibid., p. 49.
[22] Ibid., p. 50.
[23] "Brazilian Wetlands Defender Commits Suicide in Environmental Protest," *Associated Press*, 15 November 2005.
[24] Kaltner et al., op. cit. note 15, pp. 50–51.
[25] Fred Pearce, "Forests Paying the Price for Biofuels," *New Scientist*, 22 November 2005.
[26] Ibid.
[27] Barbara Bramble, Senior Program Advisor for International Affairs, National Wildlife Federation, Washington, DC, e-mail to Janet Sawin, Worldwatch Institute, 23 February 2006.
[28] R. Schneider et al., *Sustainable Amazon: Limitations and Opportunities for Rural Development* (Washington, DC: World Bank & Imazon, Brazil: 2000), cited in Anne Casson, "Oil Palm, Soybeans & Critical Habitat Loss," review prepared for the WWF Forest Conversion Initiative (Zurich: August 2003), p. 17.
[29] Maria Pia Palermo, "Brazil Losing Fight to Save the Amazon," *Reuters*, 23 May 2005.
[30] Rob Glastra, Erik Wakker, and Wolfgang Richert, "Oil Palm Plantations and Deforestation in Indonesia. What Role Do Europe and Germany Play?" (Zurich: WWF Germany, with WWF Indonesia and WWF Switzerland, November 2002), at www.panda.org/downloads/forests/oilpalmindonesia.pdf; Pearce, op. cit. note 25; UK Department for Transportation, "Towards a UK Strategy for Biofuels—Public Consultation," (London, 26 April 2004), at www.dft.gov.uk/stellent/groups/dft_roads/documents/page/dft_roads_028393.hcsp.
[31] Clay, op. cit. note 16, pp. 211–18.
[32] Ibid, p. 219.

[33] Ed Matthew, "Palm Oil is Killing Off the Orang-utan," Scotsman.com, 24 September 2005; Friends of the Earth International et al., "The Oil for Ape Scandal—How palm oil is threatening the orang-utan" (Amsterdam: 2005).
[34] E.P. Deurwaarder, "Overview and Analysis of National Reports on the EU Biofuel Directive: Prospects and Barriers for 2005," Sixth Research Framework Programme of the European Union (Petten, The Netherlands: Energy Research Centre of the Netherlands, May 2005), p. 25.
[35] "No Evidence of Threat to Wildlife Caused by Oil Palm Plantations," Bernama.com (Malaysian National News Agency), 12 October 2005.
[36] David Turley, scientist and co-author of a study commissioned by the Home Grown Cereals Authority in the UK and completed early 2005, cited in "UK Study Sees Biofuel Yielding Mixed Green Impact," *Reuters*, 17 May 2005.
[37] Tanzania Traditional Energy Development and Environment Organisation (TaTEDO), "Biofuels for Transportation in Tanzania Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for GTZ (Dar es Salaam: September 2005), p. 94.
[38] Michael Duffy, Professor of Economics, Iowa State University, e-mails to Peter Stair, Worldwatch Institute, 2 December 2005.
[39] European Commission (EC), Directorate-General for Energy and Transport, "Promoting Biofuels in Europe" (Brussels: 2004), p. 6.
[40] Uwe Fritsche, Öko-Institut, Darmstadt, Germany, reviewer comments, 9 March 2006.
[41] See, for example, G.W. Burton, "Improved recurrent restricted phenotypic selection increases bahiagrass forage yields," *Crop Science*, vol. 22 (1982), pp. 1058–61, and G.W. Burton and B.G. Mullinix, "Yield distributions of spaced plants within Pensacola bahiagrass populations developed by recurrent restricted phenotypic selection," *Crop Science*, 38 pp. 333–336, 1998, cited in Nathanael Greene et al, *Growing Energy: How Biofuels Can Help End America's Oil Dependence* (Washington, DC: Natural Resources Defense Council, December 2004), p. 26.
[42] EC, "Annex to the Communication from the Commission: An EU Strategy for Biofuels, Impact Assessment" Commission Staff Working Document (Brussels: 2006), p. 17.
[43] Clay, op. cit. note 16, pp. 211, 412.
[44] Sidebar 12–1 is based on the following sources: John Vidal, "America's Masterplan is to Force GM Food on the World," *The Guardian*, 13 February 2006; David Cullen, "Biggest Study of GMO Finds Impact on Birds, Bees," *Reuters*, 22 March 2005; "Most in US Would Shun Labeled Biotech Foods – Poll," *Reuters*, 16 July 2003; David Cullen, "UK Gene Crop Test Results Fuel Demands for Ban," *Reuters*, 17 October 2003; Norman E. Borlaug, "Ending World Hunger: The Promise of Biotechnology and the Threat of Anti-Science Zealotry," *Plant Physiology*, vol. 124, no. 2 (October 2000), pp. 487–490; G. Conway and G. Toennisessen, "Feeding the World in the Twenty-First Century," *Nature*, December 1999, pp. C55–C58; Interacademies, "Transgenic Plants and World Agriculture," report prepared under the auspices of seven Academies of Science (Brazil, China, India, Mexico, Third World, UK, US) (Washington, DC: 2000); Sylvie Bonny, "Why are Most Europeans Opposed to GMOs? Factors Explaining Rejection in France and Europe," *Electronic Journal of Biotechnology*, 15 April 2003, available at www.ejbiotechnology.info/content/vol6/issue1/full/4/; Clay, op. cit. note 16, p.181; Charles M. Benbrook, "Genetically Engineered Crops and Pesticide Use in the United States: The First Nine Years," Biotech-Info Technical Paper No. 7 (Sand Point, ID: Northwest Science and Environmental Policy Center, October 2004; Dennis Keeney and Steve Suppan, Institute for Agriculture and Trade Policy (IATP), comments provided in Jim Kleinschmit, IATP, e-mail to Janet Sawin, Worldwatch Institute, 21 February 2006; Paul Brown and John Vidal, "Two GM Crops Face Ban for Damaging Wildlife," *The Guardian*, 17 October 2003; Michael McCarthy, "Wildlife Fear Leaves GM Safety Debate Unresolved," *The Independent*, 22 July 2003; : Pew Initiative on Food and Biotechnology, "Have Transgenes—Will Travel: Issues Raised by the Gene Flow from Genetically Engineered Crops" (Washington, DC, August 2003); Organic Consumers Association, "How Great is the Impact of GMOs on Organic?" (Finland, MN: June 2005); Lilian Joensen and Stella Semino, "Argentina's Torrid Love Affair with the Soybean," *Seedling* (GRAIN), October 2004 (excerpt from Lilian Joensen, Stella Semino, and Helena Paul, "Argentina: Case Study on the Impact of RoundUp Ready Soya" (Brighton, UK: Rural Reflection Group, Argentina and EcoNexus, UK, March 2005); Manoah Esipisu, "Gene Crops No Help to Africa So Far—Report," *Reuters*, 11 January 2006; in Greene et al., op. cit. note 41, p. 44.

[45] The Energy and Resources Institute (TERI), "Biofuel for Transportation: India Country Study on Potential and Implications for Sustainable Agriculture and Energy," report prepared for GTZ (New Delhi: October 2005), p. 60.
[46] Ibid.
[47] Mali-Folkecenter, "The Jatropha Plant as a Tool for Combating Desertification, Poverty Alleviation, & Provision of Clean Energy Services to Local Women" (Bamako, Mali: May 2004).
[48] Robin L. Graham, Wei Liu, and Burton C. English, "The Environmental Benefits of Cellulosic Energy Crops at a Landscape Scale," in *Environmental Enhancement through Agriculture: Proceedings of a Conference*, Tufts University, Boston, MA, 15–17 November 1995.
[49] Carlo N. Hamelinck and Andre P.C. Faaij, "Outlook for Advanced Biofuels," *Energy Policy*, article in press, 2006 (provided by A. Faaij).
[50] Kirsten Wiegmann and Uwe R. Fritsche, with Berien Elbersen, "Environmentally Compatible Biomass Potential from Agriculture" (Darmstadt: Öko-Institut, February 2006), pp. 43–63.
[51] Thomas F. Riesing, "Cultivating Algae for Liquid Fuel Production," *The Permaculture Activist*, no. 59, March 2006, p. 48.
[52] John Sheehan et al., "A Look Back at the U.S. Department of Energy's Aquatic Species Program—Biodiesel from Algae, Closeout Report" (Golden, CO: NREL, July 1998), at www.nrel.gov/docs/legosti/fy98/24190.pdf.
[53] Based on 11,000 tons of garbage daily, and 40,000 tons filling 0.4 hectare (one acre) of landfill space. Data from Lester R. Brown, "New York: Garbage Capital of the World," Eco-Economy Update (Washington, DC: Earth Policy Institute, 17 April 2002.
[54] Agricultural waste from Brad Lemley, "Anything into Oil," *Discover*, May 2003; world oil consumption from BP, *Statistical Review of World Energy 2005* (London: 2005), p. 9.
[55] Jim Cook and Jan Beyea, "An Analysis of the Environmental Impacts of Energy Crops in the USA: Methodologies, Conclusions and Recommendations" (Washington, DC: National Audubon Society, undated), p. 5, at www.panix.com/~jimcook/data/ec-workshop.html, viewed 18 July 2005.
[56] M.J. Bullard, D.G. Christian, and C. Wilkins, "Quantifying Biomass Production in Crops Grown for energy," ETSU B CR/0038-00-00 (Harwell, Didcot, Oxon: AEA Technology Environment, 1996), pp. 61–63; O.J.F. Santos, "Environmental Aspects of Miscanthus Production," in M.B. Jones and M. Walsh, eds., *Miscanthus for Energy and Fibre* (London, James and James: 2001), pp. 46–47, cited in D.S. Powlson, A.B. Riche and I. Shield, "Biofuels and Other Approaches for Decreasing Fossil Fuel Emissions from Agriculture," *Annals of Applied Biology*, vol. 146 (2005), pp. 193–201.
[57] David W. Sample, Laura Paine, and Amber Roth, "Harvested Switchgrass Fields Provide Habitat for Declining Grassland Birds," paper presented at BioEnergy '98: Expanding Bioenergy Partnerships, Madison, WI, 4–8 October 1998.
[58] Graham, Liu, and English, op. cit. note 48; A. Schiller and V.R. Tolbert, "Hardwood Energy Crops and Wildlife Diversity: Investigating Potential Benefits for Breeding Birds and Small Mammals" (Oak Ridge, TN: Oak Ridge Associated Universities and Biofuels Feedstock Development Program, Oak Ridge National Laboratory (ORNL), 1996), available at http://bioenergy.ornl.gov/papers/bioen96/schiler1.html.
[59] TaTEDO, op. cit. note 37, p. 94.
[60] Graham, Liu, and English, op. cit. note 48.
[61] Robert D. Perlack et al., "Biomass Fuel from Woody Crops for Electric Power Generation" (Oak Ridge, TN: ORNL, 21 September 1995), at http://bioenergy.ornl.gov/reports/fuelwood/toc.html.
[62] Cook and Beyea, op. cit. note 55; Schiller and Tolbert, op. cit. note 58.
[63] Perlack et al., op. cit. note 61.
[64] TERI, op. cit. note 45, p. 60; UK Department for Transporation, op. cit. note 30; Graham, Liu, and English, op. cit. note 48.
[65] Schiller and Tolbert, op. cit. note 58.
[66] International Energy Agency (IEA), "Sustainable Production of Woody Biomass for Energy," a position paper prepared for IEA Bioenergy (Paris: 2002), p, 8.
[67] United Nations Environment Programme (UNEP), *Global Environment Outlook, GEO-2000* (Nairobi 2000).
[68] Wiegmann and Fritsche, with Elbersen, op. cit. note 50, p. 46.
[69] Ibid., p. 57.
[70] IEA, op. cit. note 66, p. 6.

[71] W.W. Wilhelm and J. Cushman, "Implications of Using Corn Stalks as a Biofuel Source: A Joint ARS and DOE Project," *Eos. Trans. Agu,,* vol. 84, no. 46 (2003), available at ars.usda.gov/research/publications/publications.htm?SEQ_NO_115=166979.
[72] TaTEDO, op. cit. note 37, p. 95; Wiegmann and Fritsche, with Elbersen, op. cit. note 50, p. 46.
[73] Perlack et al. op. cit. note 61.
[74] Masami Kojima and Todd Johnson, "Potential for Biofuels for Transport in Developing Countries" (Washington DC: Worldbank, 2005), p. 56.
[75] Television Trust for the Environment, "Power Pods—India," Hands On-Ideas to Go, Series 4 (London: February 2004), at www.tve.org/ho/doc.cfm?aid=1433.
[76] TERI, op. cit. note 45, p. 57.
[77] J.W. Ranney and L.K. Mann, "Environmental Considerations in Energy Crop Production," *Biomass and Bioenergy*, vol. 6 (1994), pp. 211–228, cited in T.H. Green et al., "Environmental Impacts of Conversion of Cropland to Biomass Production," *Proceedings*, BIOENERGY '96 - The Seventh National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies, September 15–20, 1996, Nashville, Tennessee, available at bioenergy.ornl.gov/papers/bioen96/green.html.
[78] Ibid.
[79] Kaltner et al., op. cit. note 15, p. 57.
[80] D. Pimentel and J. Krummel, "Biomass Energy and Soil Erosion: Assessment and Resource Costs," *Biomass*, vol. 14 (1987), pp. 15–38, cited in Green et al., op. cit. note 77.
[81] Perennial grasses and trees in S. B. McLaughlin et al., "High-Value Renewable Energy from Prairie Grasses," *Environmental Science and Technology,* vol. 36, no. 10 (2002), p. 2124; Perlack et al., op. cit. note 61, pp. 1–2, 4–5; more intensive crops from Greene et al., op. cit. note 41, pp. 28–29; TERI, op. cit. note 45, p. 57.
[82] Clay, op. cit. note 16, pp. 418–419.
[83] Green et al., op. cit. note 77.
[84] Wiegmann and Fritsche, with Elbersen, op. cit. note 50, p. 53.
[85] Ibid., p. 52.
[86] Ibid.
[87] Pests from ibid, p. 57; pest and disease resistance from Powlson, Riche and Shield, op. cit. note 56, p. 194.
[88] TERI, op. cit. note 45, p. 57.
[89] Kaltner et al., op. cit. note 15, pp. 86–87.
[90] TaTEDO, op. cit. note 37, p. 95.
[91] IEA, "Sustainable Production of Woody Biomass for Energy," a position paper prepared for IEA Bioenergy, 2002, p, 6.
[92] G.R. Benoit and M.J. Lindstrom, "Interpreting Tillage-Residue Management Effects," *Journal of Soil and Water Conservation*, March-April 1987, pp. 87–90.
[93] U.S. Department of Agriculture, Soil Quality Institute, "Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations," White Paper (Washington, DC: 4 March 2003), p. 2.
[94] Wiegmann and Fritsche, with Elbersen, op. cit. note 50.
[95] Wilhelm and Cushman, op. cit. note 71.
[96] IEA, op. cit. note 66.
[97] Graham, Liu, and English, op. cit. note 48.
[98] Sandra Postel, "Safeguarding Freshwater Ecosystems," in Worldwatch Institute, *State of the World 2006* (New York: W.W. Norton & Company, 2006), p. 52.
[99] Kojima and Johnson, op. cit. note 74, p. 25.
[100] Marcelo E. Dias De Oliveira, Burton E. Vaughan, and Edward J. Rykiel Jr., "Ethanol as Fuel: Energy, Carbon Dioxide Balances, and Ecological Footprints," *BioScience*, July 2005, p. 601.
[101] Kojima and Johnson, op. cit. note 74, p. 25.
[102] UNEP, op. cit. note 67.
[103] Michael Pollan, "When a Crop Becomes King," *New York Times*, 19 July 2002.
[104] Sidebar 12–2 is based on the following sources: natural gas and oil from Pollan, ibid; nitrogen cycle from UNEP, op. cit. note 67; World Health Organization in collaboration with United Nations Environment Programme, *Public Health Impact of Pesticides Used in Agriculture* (Geneva: 1990); palm oil and Bt corn from Clay, op. cit. note 16, p. 222, 412; Hosein Shapouri, James A. Duffield, and Michael Wang, "The Energy Balance of Corn Ethanol: An Update," Agricultural Economic Report No. 813 (Washington, DC:

USDA Office of Energy Policies and New Uses, 2002); comparison of fertilizer inputs from Wiegmann and Fritsche, with Elbersen, op. cit. note 50, p. 55; nitrogen oxides from Wuppertal Institute for Climate, Environment, and Energy, “Synopsis of German and European Experience and State of the Art of Biofuels for Transport,” report submitted to GTZ (Wuppertal, Germany: 2005), p. 31; hybrids and sugar cane pesticide use and rising herbicide use from Kojima and Johnson, op. cit. note 74, pp. 80, 128; no-till practices from Kaltner et al., op. cit. note 15, p. 120–21; low pesticide needs for energy crops from IEA, op. cit. note 66, p. 4; Powlson, Riche and Shield, op. cit. note 56; organic manure from Francis et. al., 2005, cited in TERI, op. cit. note 45, p. 56; jatropha from TERI, op, cit. note 45, p. 56; vinasse and filter cake from Coelho, op. cit. note 18, p. 14; matching with soils and yields from TaTEDO, op. cit. note 37, p. 95; careful timing and placement from University of California Agriculture and Natural Resources, “Reduce Pollution With Proper Fertilizer Timing,” at http://ucanr.org/delivers/impactview.cfm?impactnum=249&mainunitnum=0, viewed June 2005 strategies for lowering pesticide use from Edward Smeets, André Faaij, and Iris Lewandowski, “The impact of sustainability criteria on the costs and potentials of bioenergy production,” (Utrecht: Copernicus Institute, Utrecht University, May 2005), p. 61; U.S. herbicide treatment from Clay, op. cit. note 16, p. 412; pesticide use in Brazil sugar cane from Coelho, op. cit. note 18, p. 14.

[105] Powlson, Riche, and Shield, op. cit. note 56.

[106] TaTEDO, op. cit. note 37, p. 94.

[107] W. Gehua et al., “Liquid Biofuels for Transport: China Potential and Implications for Sustainable Agriculture and Energy in the 21st Century,” prepared for GTZ (Beijing: November 2005), p. 102.

[108] Green et al., op. cit. note 77; Powlson, Riche, and Shield, op. cit. note 56.

[109] Powlson, Riche, and Shield, op. cit. note 56.

[110] H.A. Lyons, S.G. Anthony and P.A. Johnson, “Impacts of increased poplar cultivation on water resources in England and Wales,” *Aspects of Applied Biology*, vol. 65 (2001), pp. 83–90, cited in TaTEDO, op. cit. note 37, p. 94.

[111] TERI, op. cit. note 45, p. 61.

[112] Ibid., pp. 58–59.

[113] Kojima and Johnson, op. cit. note74, pp. 125–26.

[114] Kaltner, et al., op. cit. note 15, p. 85.

[115] Kojima and Johnson, op. cit. note 74, p. 27.

[116] Mark Peplow, “Ethanol Production Harms Environment, Researchers Claim,” *Nature*, 1 July 2005.

[117] Kojima and Johnson, op. cit. note 74, pp. 125–26.

[118] Ibid., p. 68; I. Macedo et al., “Sugar Cane’s Energy: Twelve Studies on Brazilian Sugar Cane Agribusiness and Its Sustainability” (São Paulo: União da Agroindústria Canavieira de São Paulo, 2005), p. 142.

[119] UNEP, op. cit. note 67.

[120] For example, Markus Quirin et al., “CO_2 Mitigation through Biofuels in the Transport Sector: Status and Perspectives, Main Report” (Heidelberg: Institute for Energy and Environmental Research, August 2004) and J. Calzoni et al., “Bioenergy for Europe: Which Ones Fit Best? A Comparative Analysis for the Community,” Funded by the European Commission in the framework of the FAIR Programme (Heidelberg: Institute for Energy and Environmental Research, November 2000).

[121] Coelho, op. cit. note 18, p. 15.

[122] “No Evidence of Threat to Wildlife Caused by Oil Palm Plantations,” op. cit. note 35.

[123] TERI, op. cit. note 45, p. 61.

Chapter 13. Environmental Impacts of Biofuels Processing, Transport, and Use

[1] M.A. Delucchi, “Summary of Non-monetary Externalities of Motor Vehicle Use,” Report 9 in the series “The Annualized Social Cost of Motor Vehicle Use in the US, Based on 1990-1991 Data: Summary of Theory, Methods and Data,” draft report prepared for the Union of Concerned Scientists (UCS) (Davis, California: Institute of Transportation Studies, 1995), cited in UCS, “Subsidizing Big Oil,” at www.ucsusa.org/clean_vehicles/fuel_economy/subsidizing-big-oil.html.

[2] UCS, ibid.

[3] European Commission, “External Costs: Research Results on Socio-Environmental Damages Due to Electricity and Transport” (Brussels: 2003), p. 15.

[4] Environmental Defense, "Oil Refining-Main Page" (Washington, DC: posted 4 May 1999), at www.environmentaldefense.org/article.cfm?ContentID=1537.
[5] P.C. Sherertz, "Petroleum Products" (Richmond, VA: Virginia Department of Health, 30 June 1998), at www.vdh.state.va.us/HHControl/petrofac.PDF.
[6] M. Mann and P. Spath, "Life Cycle Assessment of a Biomass Gasification Combined-Cycle Gasification System" (Golden, CO: National Renewable Energy Laboratory (NREL), December 1997), p. 88.
[7] D. Doniger, "Oil Companies, Making Record Profits, Seek Environmental Rollbacks" (New York: Natural Resources Defense Council (NRDC), 8 May 2001).
[8] U.S. Department of Energy (DOE), Energy Information Administration, *Annual Energy Review 2001* (Washington, DC: 2002), p. 49.
[9] Energetics, Inc., "Energy and Environmental Profile of the U.S. Petroleum Refining Industry," report prepared for DOE (Washington, DC: DOE, Office of Industrial Technologies, 1998), cited in Nathanael Greene et al., *Growing Energy: How Biofuels Can Help End America's Oil Dependence* (Washington, DC: NRDC, December 2004), p. 43.
[10] E.O. van Ravenswaay, "Pollution Prevention Case Study on Petroleum" (East Lansing, MI: Michigan State University, 15 October 1998), at www.msu.edu/course/eep/255/PetroleumP2CaseStudy.htm.
[11] Robert Collier, "Fueling America: Oil's Dirty Future—Canadian Oil Sands: Vast Reserves Second to Saudi Arabia Will Keep America Moving, But at a Steep Environmental Cost," *San Francisco Gate*, 22 May 2005.
[12] Colorado Environmental Coalition et al., "Oil Shale and Tar Sands Resources Leasing Programmatic EIS; Scoping Comments," comments submitted to the U.S. Bureau of Land Management, Argonne National Laboratory, 31 January 2006, pp. 18–43.
[13] Mann and Spath, op. cit. note 6, pp. 53–65.
[14] For a list of the biggest oil spills of the last thirty years, see The Mariner Group, "History," at www.marinergroup.com/oil-spill-history.htm. F.A. Leighton, "Petroleum Oils and Wildlife" (Saskatoon, SC: Canadian Cooperative Wildlife Health Centre, Western College of Veterinary Medicine, University of Saskatchewan, May 2000), at http://wildlife1.usask.ca/ccwhc2003/wildlife_health_topics/oil/oil1.php; Michael Renner, "Oil Spills Decline," in Worldwatch Institute, *Vital Signs 2002* (New York: W.W. Norton & Company, 2002).
[15] "Companies in Crisis—What Not to Do When It All Goes Wrong: Exxon Mobil and the Exxon Valdez," at www.mallenbaker.net/csr/CSRfiles/crisis03.html, viewed 4 March 2006.
[16] Ilinca Bazilescu and Bret Lyhus, "Russia Oil Spill," Trade and Environment Database Case Studies (Washington, DC: American University, 11 January 1997), at http://gurukul.ucc.american.edu/ted/KOMI.HTM.
[17] United Kingdom Onshore Pipeline Operators' Association, "Worldwide Pipeline Incidents–April 2002," at www.ukopa.co.uk/publications/pdf/020035.pdf, viewed 5 March 2006.
[18] Mann and Spath, op. cit. note 6, p. 93.
[19] Pennsylvania Department of Environmental Protection, "Automobile Emissions: An Overview," at www.dep.state.pa.us/dep/subject/pubs/arr/aq/fs1829.pdf, viewed June 2005.
[20] Abt Associates Inc., "The Particulate Related Health Benefits of Reducing Power Plant Emissions" (Bethesda, MD: October 2000), at www.abtassociates.com/reports/particulate-related.pdf.
[21] Masami Kojima and Todd Johnson, "Potential for Biofuels for Transport in Developing Countries" (Washington DC: Worldbank, 2005), p. 73.
[22] Table 13–1 is based on the following sources: SO_2 exposure from Stan McMillen et al., "Biodiesel: Fuel for Thought, Fuel for Connecticut's Future" (Storrs, CT: Connecticut Center for Economic Analysis, University of Connecticut, 24 March 2005), p. 33; Kojima and Johnson, op. cit. note 21, pp. 63–73, 74; particulate matter deaths from U.S. Environmental Protection Agency (EPA), cited in McMillen et al., op. cit. this note, p. 33l lead poisoning from Paul R. Epstein and Jesse Selber, eds., *Oil: A Life Cycle Analysis of its Health and Environmental Impacts* (Cambridge, MA: The Center for Health and the Global Environment, Harvard Medical School, Harvard University, March 2002).
[23] John Sheehan et al., "Life Cycle Inventory of Biodiesel and Petroleum Diesel," prepared for the U.S. Department of Agriculture (USDA) and DOE (Golden, CO: NREL, May 1998), p. 134.
[24] Ibid.
[25] Ibid., p. 135.

[26] Wang Gehua et al., "Liquid Biofuels for Transport: China Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," draft report prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Beijing: 2005), p. 67.
[27] Marcelo E. Dias De Oliveira, Burton E. Vaughan, and Edward J. Rykiel Jr., "Ethanol as Fuel: Energy, Carbon Dioxide Balances, and Ecological Footprints," *BioScience*, July 2005, p. 601, cited in Mark Peplow, "Alcohol Fuels Not so Green," *Nature*, 1 July 2005.
[28] Gehua et al., op. cit. note 26, p. 67.
[29] Processing in Martin Tampier et al., "Identifying Environmentally Preferable Uses for Biomass Resources, Stage 2 Report: Life-Cycle GHG Emissions Reduction Benefits of Selected Feedstock-to-Product Threads," prepared for Natural Resources Canada and National Research Council Canada (North Vancouver, BC: Envirochem Services Inc., 19 July 2004), p. 32; Greene et al., op. cit. note 9, p. 43.
[30] Jason Clay, *World Agriculture and Environment* (Washington, DC: Island Press, 2004), p. 162.
[31] Kojima and Johnson. op. cit. note 21, p. 72.
[32] William S. Saint, "Farming for Energy: Social Options under Brazil's National Alcohol Programme." *World Development*, vol. 10, no. 3 (1982), pp. 223–38, cited in Kojima and Johnson, op. cit. note 21, p. 27.
[33] Kojima and Johnson, op. cit. note 21, p. 72.
[34] I. Macedo et al., "Sugar Cane's Energy: Twelve Studies on Brazilian Sugar Cane Agribusiness and Its Sustainability" (São Paulo: União da Agroindústria Canavieira de São Paulo, 2005), p. 167.
[35] William Burnquist, Centro de Tecnologia Canavieira (CTC), Brazil, conversation with Suzanne Hunt and Peter Stair, Worldwatch Institute, 28 October 2005.
[36] Sergio Pacca, University of São Paulo, reviewer comments, 13 February 2006.
[37] Kojima and Johnson, op. cit. note 21, pp. 25, 72, 127.
[38] Perry Beeman, "Ethanol Plans Among Iowa's Polluters," *Des Moines Register*, 11 September 2005.
[39] Novozymes and BBI International, "Fuel Ethanol Production: Technological and Environmental Improvements, Its History, Its Advancements, Its Future," 26 June 2002, cited in Kojima and Johnson, op. cit. note 21, p. 72.
[40] Greene et al., op. cit. note 9, p. 43; Energetics, Inc., op. cit. note 9.
[41] Novozymes and BBI International, op. cit. note 39.
[42] Greene et al., op. cit. note 9, p. 43.
[43] Ibid.
[44] "Illinois Ethanol Producer Must Install Air Pollution Controls," *Environment News Service*, 24 December 2005.
[45] Beeman, op. cit. note 38.
[46] Jim Core, "New Method Simplifies Biodiesel Production," *Agricultural Research*, April 2005.
[47] Sheehan et al., op. cit. note 23, p. 124.
[48] Greene et al., op. cit. note 9, p. 42.
[49] Kojima and Johnson, op. cit. note 21, p. 32.
[50] Beeman, op. cit. note 38; EPA, "Ethanol Plant Clean Air Act Enforcement Initiative" (Washington, DC: updated 1 September 2005), at www.epa.gov/compliance/resources/cases/civil/caa/ethanol/; Greene et al., op. cit. note 9, pp. 41–42.
[51] Novozymes and BBI International, op. cit. note 39.
[52] Greene et al., op. cit. note 9, p. 42.
[53] Kojima and Johnson, op. cit. note 21, p. 32.
[54] Greene et al., op. cit. note 9, p. 42.
[55] Kojima and Johnson, op. cit. note 21, p. 24.
[56] Tanzania Traditional Energy Development and Environment Organisation (TaTEDO), "Biofuels for Transportation in Tanzania Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," draft report for GTZ (Dar es Salaam: September 2005), p. 95.
[57] Lew Fulton et al., *Biofuels for Transport: An International Perspective* (Paris: IEA, 2004), p. 111.
[58] Northeast States for Coordinated Air Use Management, "Health, Environmental, and Economic Impacts of Adding Ethanol to Gasoline in the Northeast States, Volume 3: Water Resources and Associated Health Impacts" (Lowell, MA: New England Interstate Water Pollution Control Commission, 2001), cited in Greene et al., op. cit. note 9, p. 52; The Energy and Resources Institute (TERI), "Biofuel for

Transportation: India Country Study on Potential and Implications for Sustainable Agriculture and Energy," report prepared for GTZ (New Delhi: October 2005), p. 59.
[59] Randall von Wedel, "Technical Handbook for Marine Biodiesel in Recreational Boats" (Point Richmond, CA: CytoCulture International: Second Edition, 1999), at www.cytoculture.com/Biodiesel%20Handbook.htm.
[60] Gehua et al., op. cit. note 26, pp. 101–02.
[61] von Wedel, op. cit. note 59.
[62] Northeast States for Coordinated Air Use Management, op. cit. note 58.
[63] Ibid.
[64] Clean Air Task Force et al., "Prevention of Air Pollution from Ships: Reducing Shipping Emissions of Air Pollution—Feasible and Cost-Effective Options," submitted by Friends of the Earth International to the Marine Environment Protection Committee, International Maritime Organization, 7 April 2005, Annex, pp. 4–8.
[65] Ibid., p. 1.
[66] Greene et al., op. cit. note 9, pp. 49–51.
[67] Fulton et al., op. cit. note 57, p. 113.
[68] Where the RVP peaks depends on characteristics of the base gasoline; refiners can remove more of the smaller molecules in gasoline when blending it with ethanol to keep vapor pressure low.
[69] Northeast States for Coordinated Air Use Management, op. cit. note 58; Greene et al., op. cit. note 9, pp. 49–51; C. Hammel-Smith et al., "Issues Associated with the Use of Higher Ethanol Blends (E17-E24)" (Golden, CO, NREL: October 2002, pp. ii, 11–12.
[70] Fulton et al., op. cit. note 57, p. 113.
[71] Reformulated gasoline is a gasoline that is blended to burn more cleanly and thereby reduce smog-forming and toxic pollutants.
[72] Steven J. Brisby, Manager, Fuels Section, Stationary Source Division, California Air Resources Board, e-mail to Janet Sawin, Worldwatch Institute, 1 March 2006.
[73] Ibid.
[74] Kojima and Johnson, op. cit. note 21, p.5.
[75] Fulton et al., op. cit. note 57, pp. 116–18.
[76] Kojima and Johnson, op. cit. note 21, pp. 20, 78; Gehua et al., op. cit. note 26, p. 78.
[77] Kojima and Johnson, op. cit. note 21, p. 78.
[78] Fulton et al., op. cit. note 57, p. 114.
[79] Fulton et al., op. cit note 57, pp. 114–15.
[80] I.C. Macedo, "Fuel Ethanol Production in Brazil," in *Proceeding of the First Biomass Conference of the Americas*, Burlington, Vermont, August 1993 (Golden, CO: NREL, 1993), pp. 1185–93, cited Robin L. Graham, Wei Liu, and Burton C. English, "The Environmental Benefits of Cellulosic Energy Crops at a Landscape Scale," in *Environmental Enhancement through Agriculture: Proceedings of a Conference*, Tufts University, Boston, MA, 15–17 November 1995.
[81] Fulton et al., op. cit. note 57, pp. 114–15.
[82] Ibid.
[83] Auto/Oil Air Quality Improvement Research Program (AQIRP), *Program Final Report*. January 1997, cited in Kojima and Johnson, op. cit. note 21, p. 79.
[84] Uwe R. Fritsche, Katja Hünecke, and Kirsten Wiegmann, "Criteria for Assessing Environmental, Economic, and Social Aspects of Biofuels in Developing Countries," report commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ) (Freiburg: Öko-Institut e.V., February 2005), p. 32; Fulton et al., op. cit. note 57, pp. 114–15; California Air Resources Board, "Toxic Air Contaminants, Staff Report/Executive Summary" (Sacramento: 20 November 2004, at arbis.arb.ca.gov/toxics/summary/summary.htm, cited in Greene et al., op. cit. note 9, pp. 49–51.
[85] Fulton et al., op. cit. note 57, p. 114–15.
[86] Greene et al., op. cit. note 9, pp. 49-51; Fulton et al., op. cit. note 57, pp. 114–15; Fritsche, Hünecke, and Wiegmann, op. cit. note 92, p. 32.
[87] Prakash, op. cit. note 86.
[88] Kojima and Johnson, op. cit. note 21, pp. 20, 33.
[89] Ibid., p. 112.

[90] Kojima and Johnson, op. cit. note 21, p. 20.
[91] C. Hammel-Smith et al., op. cit. note 67, p. ii.
[92] Ibid., pp. 120–121.
[93] São Paulo State Environment Agency (CETESB), Relatório de Qualidade do Ar no Estado de São Paulo, 2003, cited in Kojima and Johnson, op. cit. note 21.
[94] Kojima and Johnson, op. cit. note 21, p. 102.
[95] Ibid.; Suani Teixeira Coelho, "Biofuels—Advantages and Trade Barriers," presentation at the United Nations Conference on Trade and Development, Geneva, 4 February 2005, p. 10.
[96] "Denver Winter Ethanol to Stay Until 2008," *F.O. Licht's World Ethanol and Biofuels Report*, 19 December 2005.
[97] Thomas Durbin et al., "Final Report: Effects of Ethanol and Volatility Parameters on Exhaust Emissions," CRC Project No. E-67, prepared for Coordinating Research Council, Inc., Alpharetta, GA (Riverside, CA: College of Engineering, Center for Environmental Research and Technology, University of California, 30 January 2006), pp. 47-48.
[98] Ibid.; and Chandra Prakash, "Use of Higher than 10 Volume Percent Ethanol/Gasoline Blends in Gasoline Powered Vehicles" (Ottawa: Environment Canada, 1998), available at www.ec.gc.ca/cleanair-airpur/CAOL/transport/publications/ethgas/ethgastoc.htm.
[99] Kojima and Johnson, op. cit. note 21, p. 78.
[100] K.S. Tyson, C.J. Riley, and K.K. Humphreys, "Fuel Cycle Evaluations of Biomass-Ethanol and Reformulated Gasoline" (Golden, CO: NREL, 1993), cited in Graham, Liu, and English, op. cit. note 88.
[101] Fulton et al., op. cit. note 57, p. 116.
[102] Jim Easterly, Easterly Consulting, e-mail to Suzanne Hunt, Worldwatch Institute, 4 March 2006; Marc Goodman, QSS Group, e-mail to Sergio C. Trindade, SE2T International, Ltd., 22 February 2006.
[103] Easterly, ibid.
[104] Goodman, op. cit. note 100.
[105] Greene et al., op. cit. note 9, p. 51; Gehua et al., op. cit. note 26, p. 101; TERI, op. cit. note 58, p. 57.
[106] Fulton et al., op. cit. note 57, p. 116.
[107] EPA, "A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions, Draft Technical Report," (Washington, DC: October 2002).
[108] K. Becker and G. Francis, "Biodiesel from Jatropha plantations on degraded land" (Stuttgart: University of Hohenheim, 2005), cited in TERI, op. cit. note 58, p. 58.
[109] Kojima and Johnson, op. cit. note 21, p. 81.
[110] J.R. Pedersen, A. Ingemarsson, and J.O. Olsson, "Oxidation of Rapeseed Oil, Rapeseed Methyl Ester (RME) and Diesel Fuel Studied with GC/MS," *Chemosphere*, vol. 38, no. 11 (1999), pp. 2467–74, cited in Jürgen Krahl et al., "Comparison of biodiesel with different diesel fuels regarding exhaust gas emissions and health effects," 2001, available at www.ufop.de/downloads/Biodiesel_comparison.pdf.
[111] Krahl et al., ibid.
[112] Ibid.
[113] Figure 13–1 from Fulton et al., op. cit. note 57.
[114] Liezzel M. Pascual and Raymond R. Tan, "Comparative Life Cycle Assessment of Coconut Biodiesel and Conventional Diesel for Philippine Automotive Transportation and Industrial Boiler Application" (Manila: College of Engineering, De La Salle University), p. 6, available at www.lcacenter.org/InLCA2004/papers/Pascual_L_paper.pdf.
[115] EPA, "Health and Environmental Impacts of NOx," at www.epa.gov/air/urbanair/nox/hlth.html; Greene et al., op. cit. note 9, p. 49.
[116] Kojima and Johnson, op. cit. note 21, p. 78.
[117] EPA, "EPA Upholds Reformulated Gas Requirement in California, New York, and Connecticut," press release (Washington, DC: 2 June 2005).
[118] Roland Hwang, Vehicle Policy Director, Natural Resources Defense Council, San Francisco, CA, e-mail to Janet Sawin, Worldwatch Institute, 12 March 2006.
[119] Fulton et al., op. cit. note 57, pp. 111–14.
[120] Robert McCormick, NREL, Golden, CO, e-mail to Peter Stair, Worldwatch Institute, 20 July 2005.
[121] Robert McCormick, "Effects of Biodiesel on NOx Emissions," presentation to ARB Biodiesel Workgroup, National Renewable Energy Laboratory, Golden, CO, 8 June 2005.
[122] Auto/Oil Air Quality Improvement Research Program (AQIRP), op. cit. note 81.

[123] TERI, op. cit. note 58, p. 58.
[124] Greene et al., op. cit. note 9, p. 49.
[125] Fulton et al., op. cit. note 57, p. 118.
[126] McCormick, op. cit. note 115.
[127] Manufacturers of Emissions Controls Association, "Clean Air Facts: Emission Control for Diesel Engines," (Washington, DC: undated), at www.meca.org/galleries/default-file/dieselfact%200106.pdf.
[128] *DieselNet News*, May 2005, cited in *AMFI Newsletter* (Advanced Motor Fuels Information), October 2005, available at http://virtual.vtt.fi/virtual/amf/pdf/amfinewsletter2005_4october.pdf.
[129] *Miljöfordon Newsletter* No.4 (2005), from www.ufop.de, www.all4engineers.com, cited in *AMFI Newsletter*, ibid.
[130] Sean Sinico, "Fill it Up with Natural," dw-world.de, 22 September 2005, at hwww.dw-world.de/dw/article/0,2144,1717299,00.html.
[131] Ibid.
[132] Ibid; Association of the German Biofuel Industry from Karin Retzlaff of the Association of the German Biofuel Industry, cited in ibid.
[133] R.L. McCormick, "NOx Solutions for Biodiesel" (Golden, CO: NREL and Colorado Institute for Fuels and Engine Research, Colorado School of Mines, February 2003), p. 21; National Biodiesel Board, "Study Shows NOx Emissions Reductions in Biodiesel Blends with Additive," press release (Jefferson City, MO: 4 February 2004); USDA from M.A. Hess et al., "The Effect of Antioxidant Addition on NOx Emissions from Biodiesel," *Energy and Fuels*, 17 March 2005, pp. 1749–54; World Energy Alternatives, "Biodiesel Emissions," at www.worldenergy.net/product/emissions.asp, viewed 29 January 2006.
[134] Developing countries in Lew Fulton, "Driving Ahead: Biofuels for Transport Around the World," *Renewable Energy World*, July-August, pp. 180–89.
[135] Kojima and Johnson, op. cit. note 21, p. 78.
[136] Ibid., p. 95.
[137] Greene et al., op. cit. note 9, p. 51.
[138] D1 Oils Plc., Web site, at www.d1plc.com.
[139] Emissions reductions from Fulton et al., op. cit. note 57, p. 111; EPA, op. cit. note 107.
[140] Newest vehicles in Greene et al., op. cit. note 9, p. v.

Chapter 14. Infrastructure Requirements

[1] Figure 14–1 is derived from the following sources: U.S. Department of Energy (DOE), Energy Information Administration (EIA) *Petroleum Supply Annual 2004, Volume 1* (Washington, DC: 2005), pp. 78–9; DOE, EIA, *International Energy Annual 2002* (Washington, DC: 2004); Agência Nacional do Petróleo e de Biocombustíveis, Superintendência de Planejamento e Pesquisa, "Volume de Petróleo Refinado nas Refinarias Nacionais (metros cúbicos)," and "Produção Nacional de Derivados de Petróleo (metros cúbicos)," 2006, at www.anp.gov.br/petro/dados_estatisticos.asp.
[2] F.J. Kaltner et al., "Liquid Biofuels for Transportation in Brazil: Potential and Implications for Sustainable Agriculture and Energy in the 21st Century," prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Rio de Janeiro: November 2005).
[3] C.E. Noon et al., "Transportation and Site Location Analysis for Regional Integrated Biomass Assessment (Riba)," in *Proceeding*s, Bioenergy '96 - The Seventh National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies, Nashville, TN, 15–20 September 1996, available at. http://bioenergy.ornl.gov/papers/bioen96/noon1.html.
[4] ASSOCANA—Departamento Agrícola, "Custo Médio Operacional da Lavoura de Cana-De-Açúcar em Reais" (Assis, Brazil: 30 September 2005), at www.assocana.com.br/custo.html.
[5] U.S. Department of Agriculture (USDA), Transportation and Marketing Programs/Transportation Services Branch, *Grain Transportation Report* (Washington, DC: 22 December 2005).
[6] Table 14–1 from ibid.
[7] Noon et al., op. cit. note 3.
[8] Table 14–2 from Lew Fulton et al., *Biofuels for Transport: An International Perspective* (Paris: International Energy Agency (IEA), 2004).
[9] Kaltner et al., op. cit. note 2.
[10] Cost estimates and Table 14–3 from Kaltner et al., op. cit. note 2; D.L. Van Dync and M.G. Blase, "Cheaper Biodiesel Through a Reduction in Transaction Costs," in proceedings of Bioenergy '98:

Expanding Bioenergy Partnerships, available at www.biodiesel.org/resources/reportsdatabase/reports/gen/19981001_gen-109.pdf.
[11] Kaltner et al., op. cit. note 2.
[12] "Malaysia to Boost Palm Oil Output by 25% by 2010," *F.O. Licht's World Ethanol and Biofuels Report*, 27 January 2006.
[13] Fulton et al., op. cit. note 8.
[14] Maryland General Assembly, Department of Legislative Services, "Environment - Fast-Fill Compressed Natural Gas Station Program," Senate Bill 163 (Annapolis: 1 July 2003), at http://mlis.state.md.us/2003rs/fnotes/bil_0003/sb0163.doc.
[15] Fulton et al., op. cit. note 8, p. 90.
[16] Kaltner et al., op. cit. note 2.
[17] Fueling stations from National Petroleum News (May 2005) as quoted by EIA. National Ethanol Vehicle Coalition, "How many E85 compatible vehicles are on American roads today?," at www.e85fuel.com/e85101/faqs/number_ffvs.php, viewed 10 March 2006.
[18] "Petrobras eyes ethanol pipeline with Goias," *F.O. Licht's World Ethanol and Biofuels Report*, 3 February 2006.
[19] Kaltner et al., op. cit. note 2.
[20] Ibid.
[21] Ibid.
[22] Fernando Cunha, "A Logística Atual de Transporte das Distribuidoras e a Infra-Estrutura para Exportação de Álcool," presentation at Álcool: Potencial Gerador de Divisas e Empregos seminar, O Banco Nacional de Desenvolvimento Econômico e Social (BNDES), 25–26 August 2003, at www.bndes.gov.br/conhecimento/publicacoes/catalogo/s_alcool.asp
[23] Transpetro, "Condições Gerais de Serviço – Álcool" (Rio de Janeiro: November 2005), at www.transpetro.com.br/portugues/negocios/dutosTerminais/files/CGSA.pdf.
[24] Renewable Fuels Association (RFA), "Industry Statistics," at www.ethanolrfa.org/industry/statistics/#A, viewed 10 March 2006.
[25] F.O. Licht, cited RFA, *Homegrown for the Homeland: Industry Outlook 2005* (Washington, DC: 2005), p. 14.
[26] Table 14–4 from Downstream Alternatives Inc. (DAI), "Infrastructure Requirements for an Expanded Fuel Ethanol Industry" (Oak Ridge, TN: Oak Ridge National Laboratory Ethanol Project, January 2002).
[27] Ibid.
[28] Table 14–5 derived from the following sources: low-end data from Fulton et al., op. cit. note 8; high-end data from DAI, op. cit. note 26.
[29] DAI, op. cit. note 26.
[30] Table 14–6 derived from Fulton et al., op. cit. note 8 and Kaltner et al., op. cit. note 2.
[31] Estimate of 85 percent from UNICA, "Brasil Agroindustria da Cana de Acucar" (São Paulo: Uniao da Agroindustria Canavieira do Estado de São Paulo, 2005); 33 percent from A.J. Lepach, "Perspectivas Futuras Para o Etanol Combustível. Etanol CombustívelÇ Balanço e Perspectivas," Evento Comemorativo dos 30 Anos da Criação do Proálcool, 16–17 November 2005, Auditório da Faculdade de Ciências Médicas, University of Campinas, Campinas, Brazil, available at www.nipeunicamp.org.br/proalcool/Palestras/17/Andre%20j.ppt.
[32] DAI, op. cit. note 26.
[33] Donald Van Dyne and Melvin Blasé, "Cheaper Biodiesel through a Reduction in Transaction Costs," presentation at BioEnergy '98, Madison, WI, 4 October 1998.
[34] K. Damen and A. Faaij, "A Life Cycle Inventory of Existing Biomass Import Chains for 'Green Electricity' Production," prepared for Essent Energy (Utrecht: Copernicus Institute, Department of Science, Technology and Society, Utrecht University, January 2003).
[35] Ibid.
[36] Figure 14–2 from USDA, *Grain Transportation Report* (Washington, DC: 15 December 2005).
[37] Ibid.

Chapter 15. Vehicle and Engine Technologies

[1] Ohio Farm Bureau Federation, "Ethanol on the right track at Indy 500," news feature (Columbus. OH: 3 June 2005).

[2] Range of 0–2 percent from Apace Research Ltd, "Intensive Field Trial of Ethanol/Petrol Blend," Energy Research and Development Council Project No. 2511 (Canberra: 1998).
[3] Autolex Consultoria Automotiva, São Paulo, Brazil, personal communication with **Alfred Szwarc**, Director, ADS Tecnologia e Desenvolvimento Sustentável, São Paulo, Brazil, 2005.
[4] Hua Hin, "Ford Launches Ethanol-compatible Car," *Mail & Guardian* online, 27 October 2005.
[5] National Ethanol Vehicle Coalition, "E85 Brochure," at www.e85fuel.com.
[6] "Ford Launches Focus Flexi-Fuel in UK," www.awknowledge.com, 6 September 2005.
[7] Alfred Szwarc, Director, ADS Tecnologia e Desenvolvimento Sustentável, São Paulo, Brazil, personal communication with Worldwatch Institute, 2006.
[8] Ibid.
[9] M. Brusstar and M. Bakenhus, "Economical, High Efficiency Engine Technologies for Alcohol Fuels," U.S. Environmental Protection Agency, National Vehicle and Emissions Laboratory, XV International Symposium on Alcohol Fuels (San Diego, CA: September 2005).
[10] Szwarc, op. cit. note 7.
[11] Scania Brasil, personal communication with **Alfred Szwarc**, Director, ADS Tecnologia e Desenvolvimento Sustentável, São Paulo, Brazil, 2001.
[12] U.S. National Renewable Energy Laboratory, "Hannepin County's Experience with Heavy-Duty Ethanol Vehicles" (Golden, CO: January 1998).
[13] G. Nagarajan et al., "Review of Ethanol in Compression Ignition Engine" (Chennai: Institute for Energy Studies, Anna University), at www.saeindia.org/saeconference/ethanolreview.htm.
[14] Ibid.
[15] National Biodiesel Board, "Summary of Recent Studies Citing Economic Attributes Resulting From the Successful Commercialization of Biodiesel in the US," reports database (Jefferson City, MO: July 1998), at www.biodiesel.org/resources/reportsdatabase/reports/gen/19980701_gen-054.pdf.
[16] C.A. Sharp, "Exhaust Emissions and Performance of Diesel Engines with Biodiesel Fuels" (San Antonio, TX: Southwest Research Institute, July 1998).
[17] U.S. Department of Energy, "Biodiesel Blends Fact Sheet" (Washington, DC: April 2005).
[18] Sharp, op. cit. note 16.
[19] Brazilian Reference Center on Biomass (CENBIO), personal information of Alfred Szwarc, UNICA, 2005
[20] Elsbett Web site, www.elsbett.com.
[21] "Reducing our dependence on oil," at www.sweedtrack.com/eflwa22a.htm.
[22] Total Corporation, "Alternative Energies, Promising New Technologies," at www.total.com/en/group/corporate_social_responsibility/future_energy/energy_supply/alternative_energies_6676.htm, viewed 10 March 2006.
[23] WestStart-CalStart, "California Biogas Industry Assessment White Paper" (Pasadena, CA: April 2005).
[24] Szwarc, op. cit. note 7.
[25] Ibid.

Chapter 16. Transfer of Technology and Expertise

[1] Figure 16–1 compiled by Sergio C. Trindade, President, SE2T International, Ltd., January 2006.
[2] Sergio C. Trindade. "Transfer of clean(er) technologies to developing countries," in R.U. Ayres and U.E. Simonis, eds., *Industrial Metabolism: Restructuring for Sustainable Development* (New York: United Nations University Press, 1994), pp. 319–336.
[3] Gavin P. Towler et al., "Development of a Sustainable Liquid Fuels Infrastructure Based on Biomass" (Des Plaines, Illinois: UOP Innovation Group, 2003).
[4] Figure 16–2 compiled by Trindade, op. cit. note 1.
[5] European Commission (EC), "Directive 2003/30/CE of the European Parliament and Council on 8 May 2003 relative to the promotion of the utilization of biofuels or of other renewable fuels in transportation," L 123/42 PT (Brussels: 8 May 2003); EC, "Directive 2003/96/CE of the European Council of 27 October 2003, restructuring the Community framework of taxation of energy products and electricity" (Brussels: 27 October 2003).
[6] "Sino-German Workshop on Energetic Utilization of Biomass," Beijing, 8–11 October 2003, at www.ipe.ac.cn/sinogerman/program.htm.

[7] Isaias Macedo, University of Campinas (UNICAMP), Campinas, São Paulo, Brazil, personal communication with Sergio C. Trindade, 27 December 2005; Lima Verde Leal and Manoel Régis, UNICAMP, personal communication with Sergio C. Trindade, SE2T International Ltd., 26 December 2005.
[8] Sergio C. Trindade, author's estimate, 2005.
[9] Sergio C. Trindade, "Beyond petroleum and towards a biomass-based sustainable energy future: opportunities for financing sustainable development and carbon trade," *Renewable Energy Partnerships for Poverty Eradication and Sustainable Development* (Partners for Africa), May 2005, p. 6.

Chapter 17. Biofuel Policies Around the World

[1] Suzanne Hunt and Janet Sawin, with Peter Stair, "Cultivating Renewable Alternatives to Oil," in Worldwatch Institute, *State of the World 2006* (New York: W.W. Norton & Company, 2006), p. 73.
[2] Share of global emissions in Lew Fulton et al., *Biofuels for Transport: An International Perspective* (Paris: 2004), p. 174.
[3] Masami Kojima and Todd Johnson, "Potential for Biofuels for Transport in Developing Countries" (Washington, DC: World Bank, October 2005), p. 126; Sustainable Palm Oil Production Principles set out 15 December 2005, at www.sustainable-palmoil.org, viewed 7 March 2006.
[4] Table 17–1 derived from the following sources: China, France, Thailand, and United States from Hunt et al., op. cit. note 1, p. 75; "Australia Aims to Exceed Biofuel Targets," *F.O. Licht's World Ethanol and Biofuels Report*, 4 January 2006; Brazil, Colombia, and Venezuela from Kelly Hearn, "Buenos Bios, How South American Biofuels are Gaining Steam, and Why that Freaks the U.S. Out," *Grist Magazine,* 15 December 2005; Canada from Ontario Ministry of Agriculture, Food and Rural Affairs, "McGuinty Government Takes Next Steps on Cleaner Air," press release (Toronto, ON: 7 October 2005); Herbert Tretter, "Development of Biodiesel in Austria," PowerPoint presentation, Austrian Energy Agency (Vienna: 28 February 2005); "Germany Sets Quotas for Biofuel in Fuel from 2007," *Reuters*, 3 May 2006; Lars Olofsson, "Swedish government embraces peak oil and looks towards biofuels," *Energy Bulletin*, 17 December 17 2005; India from Christoph Berg, "World Fuel Ethanol Analysis and Outlook" (Ratzeburg, Germany: FO Licht, April 2004); Japan from Danielle Murray, "Ethanol's Potential: Looking Beyond Corn" (Washington, DC: Earth Policy Institute, 25 June 2005); "Malaysia to Mandate B5 Biodiesel in 2008," Green Car Congress, 6 October 2005, at www.greencarcongress.com/2005/10/malaysia_to_man.html; Philippines from "Coconut-Biodiesel for All Government Vehicles, Memorandum Circular 55," PowerPoint presentation, Energy Center (Manila: 30 June 2004) and from "Coconut Biodiesel Blend Hits Local Philippine Market," Green Car Congress, 13 August 2005, www.greencarcongress.com/2005/08/coconut_biodies.html; "Minnesota Aims to be Saudi Arabia of Renewable Fuels," *Environment News Service*,18 May 2005; Jeff Blend and Howard Haines, "Economic Effects of Increased Ethanol Use in Montana" (Helena, MT: Montana Department of Environmental Quality, Air Energy and Pollution Prevention Bureau, 5 January 2005), at http://deq.mt.gov/Energy/bioenergy/ethanolUseInMT.asp.
[5] Sivan Kartha, Gerald Leach, and Sudhir Chella Rajan*, Advancing Bioenergy for Sustainable Development. Guideline for Policymakers and Investors. Volumes I, II, and III* (Washington, DC: World Bank Energy Sector Management Assistance Program (ESMAP), April 2005), p. 159; Francis Johnson, e-mail communication with Suzanne Hunt, Worldwatch Institute, 14 February 2006.
[6] Kojima and Johnson, op. cit. note 3.
[7] "Zimbabwe Says to Reopen Ethanol Fuel Plant" *Reuters*, 19 July 2005.
[8] "Biofuels and the International Development Agenda," *F.O. Licht's World Ethanol and Biofuels Report*, July 2005, p. 4; Stephen Karekezi, "Renewable Energy Technologies in sub-Saharan Africa," presentation to Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ, 19 April 1995.
[9] Peter Apps, "South Africa Maize Farmers See Ethanol Plant In 18 Months," *Reuters*, 15 March 2005; Sasol, "Explore Sasol: Sasol in Fuels" (Johannesburg: 12 August 2004), at www.sasol.com/sasol_internet/frontend/navigation.jsp?navid=600003&rootid=2, viewed 7 March 2006.
[10] Shaun Benton, "Government Biofuels Strategy to Cover Multiple Benefits, Says Minister," *Bua News*, 10 February 2006, at http://allafrica.com/stories/200602100545.html.
[11] D1 Oils, "South Africa—Biodiesel is a National Priority," at www.d1plc.com/global/africa_south_africa.php.

[12] "Biofuels and the International Development Agenda," *F.O. Licht's World Ethanol and Biofuels Report*, 11 July 2005, at www.energyfuturecoalition.org/pubs/Biofuels%20Seminar%20FOLichts.pdf.
[13] Murray, op. cit. note 4.
[14] Commonwealth of Australia Biofuels Taskforce, "Report of the Biofuels Taskforce to the Prime Minister" (Barton, ACT: August 2005), p. 63
[15] "China to Put Corn Into Gas Tanks to Clean Up," *Reuters*, 20 October 2003.
[16] Murray, op. cit. note 4.
[17] Prodyut Bhattacharya and Bharati Joshi, "Strategies and Institutional Mechanisms for Large Scale Cultivation of Jatropha Curcas under Agroforestry in the Context of the Proposed Biofuel Policy of India," abstract in *ENVIS Bulletin on Grassland Ecosystems and Agroforestry* (Indian Institute of Forest Management), December 2003, pp. 58–72.
[18] Berg, op. cit. note 4.
[19] The Energy and Resources Institute, "Liquid Biofuels for Transportation: India Country Study on Potential and Implications for Sustainable Agriculture and Energy," report prepared for the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (Delhi: 2005), pp. 31–32.
[20] Bhattacharya and Joshi, op. cit. note 17.
[21] "Thais to Invest $20 Billion in Energy Sector in 4 Years," *Reuters*, 17 May 2005.
[22] "Coconut-Biodiesel for All Government Vehicles, Memorandum Circular 55," op. cit. note 4; "Coconut Biodiesel Blend Hits Local Philippine Market," op. cit. note 4.
[23] "Bioethanol Benefits: Energy, Environment, Employment" (Makati City: Philippine Fuel Ethanol Alliance, 2005) at www.bioethanol.com.ph/bioethanol/benefits.html, viewed 7 March 2006.
[24] Murray, op. cit. note 4.
[25] Commonwealth of Australia Biofuels Taskforce, op. cit. note 14.
[26] Murray, op. cit. note 4.
[27] Mobil Oil Australia Pty Ltd., "Mobil Submission to the Australian Government Biofuels Taskforce," June 2005, available at www.pmc.gov.au/biofuels/submissions/submission33.pdf.
[28] "Australia Aims to Exceed Biofuel Targets," op. cit. note 4.
[29] European Commission (EC), "Biomass Action Plan," draft final (Brussels: December 2005), p. 9; EC, "Directive 2003/30/EC, 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport, O.J. L123, 17/05/2003" (Brussels: 2003).
[30] "Directive 2003/30/EC of the European Parliament and of the Council of 6 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport," *Official Journal of the European Union*, 17 May 2005, p. 1.
[31] Commonwealth of Australia Biofuels Taskforce, op. cit. note 14.
[32] EC, "Directive 2003/96/EC, 27 October 2003 restructuring the Community framework for the taxation of energy products and electricity, O.J. L283, 31/10/2003" (Brussels: 2003); Wuppertal Institute for Climate, Environment, and Energy, "Synopsis of German and European Experience and State of the Art of Biofuels for Transport," report submitted to GTZ (Wuppertal, Germany: 2005), pp. 18–19.
[33] EC, "An EU Strategy for Biofuels," draft final (Brussels: 2006).
[34] EC, "Biomass Action Plan," op. cit. note 29, pp. 9–11.
[35] Ibid., p. 10.
[36] Ibid.
[37] EC, "Commission Urges New Drive to Boost Production of Biofuels," press release (Brussels: 8 February 2006).
[38] "Panorama 2004: A Look at Biofuels in Europe," (Lyon: Institute Francais Riera, 2004).
[39] Germany from "Kemira to Invest in New Technology," *Reuters*, 6 September 1999; EC, "Biomass Action Plan," op. cit. note 29.
[40] Jose Goldemberg et al., "How adequate policies can push renewables," *Energy Policy*, 22 February 2003.
[41] Hearn, op. cit. note 4.
[42] Rodrigo Augusto Rodrigues, "Biodiesel in Brazil—An Overview," PowerPoint presentation at the III German-Brazilian Workshop on Biodiesel, Fortaleza-Ceara, Brazil, 1 July 2005, at www.ahk.org.br/inwent/palestras/rodrigo_rodrigues.ppt.
[43] Angelo Bressan Filho, Director of AgriEnergy Program, Brazil Ministry of Energy, comments at Workshop and Business Forum on Sustainable Biomass Production for the World Market, University of Campinas, São Paulo, Brazil, November 2005.

[44] Hearn, op. cit. note 4.
[45] Ibid.
[46] Renewable Fuels Association, "Federal Regulations: VEETC," at www.ethanolrfa.org/policy/regulations/federal/veetc/; Renewable Energy Policy Network (REN21), "Renewables 2005: Global Status Report" (Washington, DC: Worldwatch Institute, 2005), p. 26.
[47] "Biodiesel Mandate for Navy and Marine Facilities," RenewableEnergyAccess.com, 22 March 2005.
[48] U.S. Senate, "U.S. Renewable Fuels Standard," in *Energy Policy Act of 2005*, pp. 141–172, at http://energy.senate.gov/public/_files/H6_EAS.pdf.
[49] "State Legislation Focuses on Tax Incentives for Wind, Biofuels," RenewableEnergyAccess.com, 28 April 2005.
[50] "New York Announces New Energy Plans," RenewableEnergyAccess.com*,* 19 September 2005.
[51] Governor George Pataki, "State of the State Address," 4 January 2006, at www.ny.gov/governor/2006_sos/sosaddress_text.html.
[52] Government of Manitoba, Ministry of Energy, Science and Technology, "Energy Initiatives: Ethanol Blended Fuels" (Manitoba: 2003), at www.gov.mb.ca/est/energy/initiatives/ ethanolfuels.html.
[53] Natural Resources Canada, "Government of Canada Launches Ethanol Expansion Program," press release (Ottawa: 20 October 2003).
[54] Hunt et al., op. cit. note 1, p. 63.
[55] "Tons of Sugar, But Biofuels Controversy Remains," *The Miami Herald,* 1 August 2005.
[56] Hunt et al., op. cit. note 1, p. 64.
[57] Ibid.
[58] EC, "Commission urges Luxembourg, Italy, Portugal and Slovakia to implement Biofuels Directive," press release (Brussels: 13 December 2005); EC, "An EU Strategy for Biofuels," op. cit. note 33.
[59] The Energy and Resources Institute, "Liquid Biofuels for Transportation: India country study on potential and implications for sustainable agriculture and energy," report prepared for GTZ (New Delhi: 2005), p. 67, at www.gtz.de/de/dokumente/en-biofuels-for-transportation-in-india-2005.pdf,
[60] Hugh Dent, "China: Where has all the oil gone? IEA wonders," PetroleumWorld.com, 8 December 2005.
[61] Hunt et al., op. cit. note 1, p. 73.
[62] "Executive Summary of the Brazilian Energy Initiative," presented at the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August–4 September, 2002, available at www.worldenergy.org/wec-geis/focus/wssd/goldemberg.pdf
[63] Ibid.
[64] Table 17–2 is based on the following sources: IEA Task 40: Sustainable International Bioenergy Trade Web site, at www.bioenergytrade.org; Suzanne Hunt, "Notes from Workshop and Business Forum on Sustainable Biomass Production for the World Market," organized by IEA Task 40 Sustainable Bioenergy Trade, Tasks 30 and 31, University of Campinas, São Paulo, Brazil, November 2005 (Washington, DC: 2005); United Nations Environment Programme (UNEP), Sustainable Energy Finance Initiative Web site, at www.sefi.unep.org; "The Gleneagles Communiqué" (Gleneagles, Scotland: 6-8 July 2005), at www.fco.gov.uk/Files/kfile/PostG8_Gleneagles_Communique.pdf; United Nations Commission on Trade and Development (UNCTAD), "UNCTAD Launches the Biofuels Initiative," press release (Geneva: 21 June 2005); "Global Bioenergy Partnership White Paper," prepared by the Italian Ministry for the Environment and Territory with the participation of Imperial College London, Itabia and E4tech, October 2005, p. 31.
[65] UNCTAD from Jana Gastellum, Energy Future Coalition, personal communication with Ladeene Freimuth, Freimuth Consulting, January 2006; IEA suggestion from André Faaij, and Arnaldo Walter, "Findings of the meeting," presentation at the Workshop and Business Forum on Sustainable Biomass Production for the World Market, organized by IEA Task 40 Sustainable Bioenergy Trade, Tasks 30 and 31, University of Campinas, São Paulo, Brazil, November 2005, p. 18.
[66] Kojima and Johnson, op. cit. note 3, pp. 7–8.
[67] Boris Utria, Senior Economist and Co-Chair of the Energy & Poverty Thematic Group, Energy Unit, Africa Region, World Bank, e-mail to Lauren Sorkin and Suzanne Hunt, Worldwatch Institute, 15 February 2006.
[68] Global Environment Facility Small Grants Program, "Climate Change," at http://sgp.undp.org/index.cfm?module=ActiveWeb&page=WebPage&s=foCC, viewed December 2005.
[69] UNEP, op. cit. note 64.

[70] EC, "Biomass Action Plan," op. cit. note 29, p. 10.
[71] Natsource, Environmental Services, Glossary, available at www.natsource.com/markets/index.asp, viewed January 2006.
[72] Lew Fulton, "Biofuels for Transport: An International Perspective," presentation at Conference of the Parties (COP)-10 for the UN Framework Convention on Climate Change, International Centre for Trade and Sustainable Development (ICTSD)/UNCTAD, Argentina, 14 December 2004.
[73] Ben Atkinson, "The CDM, Kyoto protocol and the sugar, ethanol and biofuels industry" (Ringwood, Hampshire, UK: Agrinergy, undated), pp. 2–3.
[74] Jodi Brown et al., "Getting on Track: Finding a Path for Transportation in the CDM," final report (Winnipeg, Manitoba, Canada: International Institute for Sustainable Development, December 2004), p. 16.
[75] Atkinson, op. cit. note 73, p. 3.
[76] Ibid.
[77] Christiana Figueres, "Policies and Programs under the CDM," 2005, at http://lists.iisd.ca:81/read/attachment/28306/1/Policies%20and%20programs%20under%20the%20CDM.pdf.
[78] World Bank Carbon Finance Unit (CFU) Web site, at www.carbonfinance.org.
[79] World Bank CFU, "Project Portfolio," at www.carbonfinance.org.
[80] World Bank CFU, op. cit. note 78.

Chapter 18. Standards and Certification Schemes

[1] Fred Pearce, "Forests paying the price for biofuels," *New Scientist*, 22 November 2005.
[2] Friends of the Earth-UK, "The Oil for Ape Scandal: How Palm Oil is Threatening the Orang-utan (London: September 2005), p. 9.
[3] Rainforest Alliance, "Sustainable Agriculture Network," at www.rainforest-alliance.org/programs/agriculture/san/index.html.
[4] Rainforest Alliance, "Standard for Sustainable Agriculture — Sustainable Agriculture Network," at www.rainforest-alliance.org/programs/agriculture/certified-crops/standards.html.
[5] International Federation of Organic Agriculture Movements, "The IFOAM Organizational Structure," at www.ifoam.org/about_ifoam/inside_ifoam/organization.html, viewed 10 March 2006.
[6] Forest Stewardship Council (FSC) Web site, at www.fsc.org.
[7] FSC, "FSC Principles and Criteria for Forest Stewardship" (Bonn: April 2004).
[8] FSC, "Policy and Standards," at www.fsc.org/en/about/policy_standards.
[9] FSC, "About FSC," at www.fsc.org/en/about/about_fsc.
[10] Goska Romanowicz, "UK and Europe push for 'right kind' of biofuels," edie.net, 3 March 2006.
[11] Ausilio Bauen et al., "Feasibility Study on Certification for a Renewable Transport Fuel Obligation," final report (London: Edinburgh Centre for Carbon Management, Ltd., Imperial College: June 2005).
[12] Roundtable on Sustainable Palm Oil (RSPO), "RSPO Adopts the Principles and Criteria for Sustainable Palm Oil Production," press release (Singapore: 23 November 2005).
[13] RSPO, "RSPO Principles and Criteria for Sustainable Palm Oil Production," public release version (Kuala Lumpur: 17 October 2005).
[14] Ibid.
[15] RSPO, "Frequently Asked Questions," at www.sustainable-palmoil.org/FAQs.htm.
[16] World Trade Organization (WTO), "Domestic Support in Agriculture: The Boxes," at www.wto.org.
[17] A. Faaij, A. Wieczorek, and M. Minnesma, "International Debate on International Biotrade; International Workshop Report," Office of Inter-Human Dimensions Programme – Industrial Transformation (IHDP-IT), the Department of Science, Technology and Society - Utrecht University and Institute for Environmental Studies - Free University of Amsterdam. (Utrecht: NOVEM, April 2003), p. 65.
[18] WTO, op. cit. note 16.
[19] Faaij, Wieczorek, and Minnesma, op. cit. note 17.
[20] Ibid.
[21] Nielmar de Oliveira, "Neither FTAA Nor EU. WTO Is Brazil's Only Hope," *Brazil Magazine,* 5 November 2004.
[22] Faaij, Wieczorek, and Minnesma, op. cit. note 17.
[23] General Agreement on Trade and Tariffs, TBT Agreement, Article 2.4.

[24] R. Howse and E. Tuerk, "The WTO Impact on Internal Regulations: A Case Study of the Canada-EC Asbestos Dispute," in G. Bermann and P.Mavroidis, eds., *Trade and Human Health and Safety* (New York: Cambridge University Press, 2006), pp. 77–117.
[25] General Agreement on Tariffs and Trade, Article III:4.
[26] WTO, "European Communities—Measures Affecting Asbestos And Asbestos-Containing Products" (Geneva: 12 March 2001), paragraph 100. This interpretation of "no less favorable treatment" was applied by the panel in the EC-Biotech case (GMOs); see para 7.2505. For more on the EC-Biotech panel ruling (interim), see Friends of the Earth-UK, "Leaked WTO report: US misled the world on 'victory,'" press release (London: 28 February 2006). More research on this topic is forthcoming and can be found at the Web site of Robert Howse, at http://faculty.law.umich.edu/rhowse.
[27] Ibid.
[28] WTO, "Canada – Certain Measures Affecting the Automotive Industry" (Geneva: 11 February 2001).
[29] Martin Juniger and Andre Faaij, "IEA Bioenergy Task 40: Country Report for the Netherlands" (Paris: IEA, July 2005), p. 23, at www.senternovem.nl/mmfiles/IEA_Task_40_Country_Report_NL_tcm24-152474.pdf.
[30] European Commission (EC), "Biomass Action Plan," draft final (Brussels: December 2005), p. 9.
[31] Iris Lewandowski and André Faaij, "Steps Towards the Development of a Certification System for Sustainable Bio-Energy Trade," FAIR Biotrade project (Utrecht: Copernicus Institute of Sustainable Development and Innovation, July 2004).
[32] Andre Faaij, Copernicus Institute, Utrecht University, e-mail to Suzanne Hunt, Worldwatch Institute, 3 March 2006.

Chapter 19. Implications for German Agriculture and Transport