Potential Environmental Impacts of Bioenergy Crop Production

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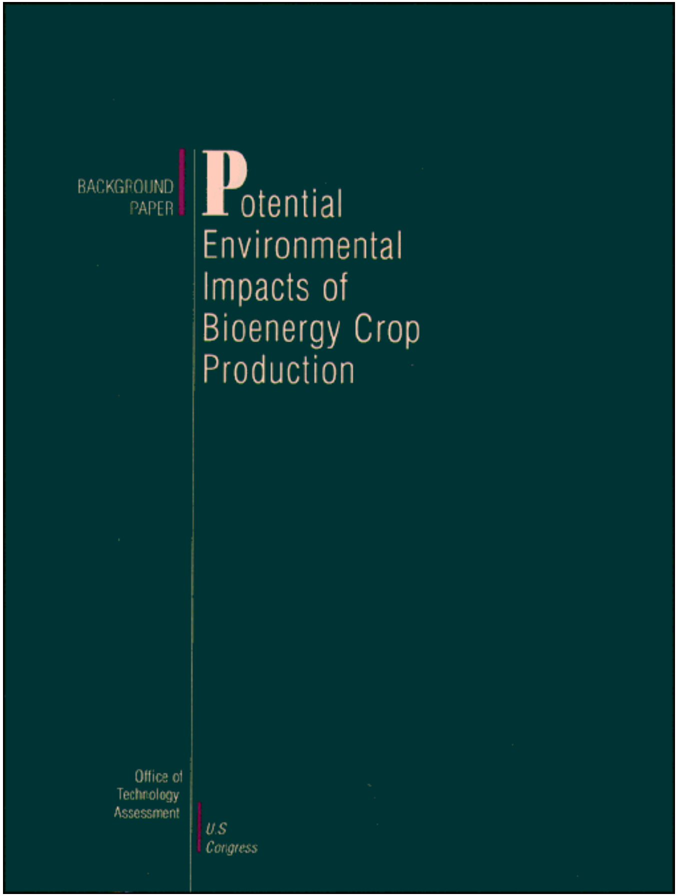

BACKGROUND
PAPER

Potential
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Impacts of
Bioenergy Crop
Production

Office of
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Assessment

U.S
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Foreword

Bioenergy crops are receiving increasing attention as a potentially low cost and large scale renewable source of energy. This report reviews how such crops could potentially affect soil quality and soil erosion, water quality, air quality, habitat for a variety of species, and the global environment. From this analysis, it examines how research and development agendas for energy crops might be expanded to better understand these impacts and to reduce potential negative environmental impacts and enhance the positive.

The report also briefly reviews other impacts of bioenergy crops, including the potential relationship between energy crops, Federal agricultural supports, rural income, and national dependence on imported fuels. In the wake of the devastating Midwest floods, energy crops might be considered as a more robust crop for flood prone areas. Although energy crops have long-term potential, much research and development remains to be done in order to understand the full range of their environmental impacts, positive and negative, and an extensive political dialogue is needed to determine how best to balance the numerous competing economic/environmental, rural/urban, regional and other interests potentially affected.

This study is the first product of a larger assessment of renewable energy technology requested by the House Committee on Science, Space, and Technology and by the House Committee on Energy and Commerce. The full assessment, to be published in 1994, will address environmental issues more broadly as well as provide detailed analyses of: renewable energy resources; the cost and performance of renewable energy technologies; commercialization issues; and policy options.

OTA appreciates the invaluable advice and assistance of the many people who contributed to this project, including the advisory panel, participants in the workshop, reviewers, and contractors. OTA, however, bears the sole responsibility for the contents of this report.

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Executive Summary

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Bioenergy crops have the potential to improve the environment, increase rural incomes, and reduce Federal budget deficits and the U.S. trade imbalance. In the wake of the devastating Midwest floods, bioenergy crops may also offer a more robust crop for flood-prone regions. To realize this broad potential, continuing research and development and environmental monitoring will be required. It will also be necessary to conduct some long-term and large-scale demonstration programs, and to address a variety of market barriers and distortions. Haphazardly implementing large-scale bioenergy programs without such a foundation could damage the environment and reduce potential economic benefits.

BACKGROUND

Bioenergy crops include annual row crops such as corn, herbaceous perennial grasses (herbaceous energy crops—HECs) such as switchgrass, and short-rotation woody crops (SRWCs) such as poplar. Annual row crops are grown in essentially the same manner as their food crop counterparts and consequently offer few or no environmental benefits over conventional agricultural practices. Because of this, annual row crops are not examined further in this report.[1]

HECs are analogous to growing hay, harvesting the crop for energy rather than for forage. SRWCs typically consist of a plantation of closely spaced (2 to 3 meters apart on a grid) trees that are harvested on a cycle of 3 to 10 years. Following harvest,

The net environmental impacts depend on what the land was previously used for, the particular energy crop, and how the crop is managed.

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[1] Energy crops (often annual row crops) exist which produce starches, sugars, oils, and other specialty plant products for energy. On a national basis, however, their energy production potential is much lower and their costs higher than for HECs and SRWCs. Consequently, they are not considered further in this report.

HECs regrow from the remaining stubble and SRWCs regrow from the remaining stumps. Such harvests may continue for 15 to 20 years or more without replanting. Fertilizer and maintenance may be required annually, however. These energy crops may be grown by farmers with only modest changes in farming practices.

A number of factors are considered in selecting specific HECs and SRWCs to be grown. These include their productivity (growth rate); robustness (ability to withstand weather, pests, and disease); efficiency in using water; overall environmental impacts (soil, water, air, habitat, greenhouse gases); and others.

HECs and SRWCs produce very large quantities of biomass—straw, wood, bark, and leaves—composed principally of cellulose and lignin.[2] These feedstocks maybe used to generate electricity or be converted to liquid fuels or combustible gases.

ENVIRONMENTAL IMPACTS

Bioenergy crops can be substituted for conventional crops or be grown on agricultural set-aside or conservation reserve program lands, degraded lands, or elsewhere. The net environmental impacts depend on what the land was previously used for, the particular energy crop, and how the crop is managed. For example, as a substitute for conventional agricultural row crops such as corn or soybeans, properly managed HECs and SRWCs can help stabilize erosive soils or perhaps filter agricultural chemicals and sediments before they reach water supplies.[3] They may help provide habitat directly or serve as buffers around, or corridors between, fragments of natural forest, wetlands, or prairie. (Such habitat benefits will, however, also depend on the particular animal species.) In contrast, substituting energy crops for hay, pasture, or well-managed Conservation Reserve Program Lands generally will have mixed environmental impacts, both positive and negative.

It is important to remember that bioenergy crops are similar to agricultural crops and should not be confused with natural habitats.[4] Current plant species under consideration for use as bioenergy crops are primarily native species that evolved in the regions where they may be used. These crops can provide greater biodiversity on a landscape level than typical agricultural crops, and thus can enhance wildlife habitat. The benefits may be transient, however, depending on the management and harvesting practices required to produce an economically viable crop.

Bioenergy can potentially also improve urban and regional air quality by reducing SO_x and NO_x. If poor-quality equipment or controls are used, however, emissions of particulate and certain organic compounds could be increased by the substitution of bioenergy for conventional fuels.

When grown on a sustainable basis,[5] bioenergy can offset emissions of greenhouse gases from fossil fuels and thus slow potential global warming. In the long-run, if greenhouse gas emissions are not reduced, potential warming may cause the

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[2] Cellulose is the fibrous material in plants and lignin is the "glue" that binds the fibers together. Because of this content, these crops are also known as lignocellulosic energy crops.

[3] To serve as a filter and to be harvested periodically for energy, energy crops may require more complex and careful management than is typical for energy crops which do not serve such demanding multiple functions.

[4] Defining "natural habitat" may be difficult and controversial because past decades—sometimes centuries-of clear cutting, selective harvesting of economically valuable trees, and fire suppression have altered many U.S. forests, often leading to an increased concentration of plant species with lower economic or ecological value. Similar alterations have occurred over many other U.S. landscapes, including prairie and wetlands. Although defining how much modification still qualifies as "natural" is thus challenging, the term will be used broadly here to include all lands that support a significant quantity and variety of indigenous plants and animals. For this report, only current or former agricultural lands or highly degraded lands are considered for energy crops.

[5] For example, as much new biomass is grown as is burned for fuel. There are also potential sequestration benefits for both soil carbon and standing biomass.

loss of natural habitats throughout the United States as well as globally.

RURAL ECONOMIC IMPACTS

Rural economies in the United States have been hard pressed for many years. Between about 1980 and 1990, the U.S. share of the world's total agricultural trade dropped from 28 percent to 21 percent. At the same time, the European share grew from about 13 percent to 19 percent. China is now the world's second largest corn exporter, and Brazil is a major exporter of soybeans. Some expect that parts of Eastern Europe and the former Soviet Union could become food exporting powerhouses in the future.[6] Roughly half of the ship-loading grain terminals in the United States are reportedly closed, about to close, or for sale.[7] Due to these pressures, there is a growing need to find alternative crops for rural agricultural communities: to provide employment, to stabilize rural incomes, and to maintain the rural infrastructure of equipment and supplies distribution and service. Bioenergy crops are one such alternative if mechanisms can be found to overcome a variety of market and institutional obstacles to their use.

FEDERAL BUDGET IMPACTS

The Federal budget is likewise under great pressure and agricultural programs, like everything else, are under increased scrutiny for savings. Currently, Federal programs to prevent soil erosion[8] and various commodity support programs to strengthen crop prices cost roughly $10 billion per year. Bioenergy crops are a potential alternative cash crop that could protect fragile soils or could be grown on lands previously idled in order to strengthen commodity crop prices. Earnings from the energy crop might then allow Federal supports to be eased while maintaining farm income. Of course, the relative environmental benefits of energy crops versus current soil conservation programs such as the Conservation Reserve Program would again depend on the specific energy crops grown and how the land was managed. The relative economic and budgetary value of producing bioenergy crops would have to be compared to potential alternative uses of the land. Designing Federal programs to achieve such ends while minimizing disruption and risk to farmers also presents challenges.

TRADE BALANCE IMPACTS

U.S. expenditures on foreign oil are currently running about $50 billion per year and are destined to increase sharply as domestic oil production continues to decline. Several U.S. electric utilities are also now importing low-sulfur coal. Bioenergy crops could potentially offset some of these imports. Although bioenergy by itself is unlikely to eliminate fuel imports, it could make a substantial contribution to our energy needs.

BASELOAD POWER

In addition to the above potential benefits, biomass energy may play a particularly important role if there is a greater emphasis in the future on using renewable forms of energy. In contrast to intermittent renewable such as solar (available when the sun shines) and wind (available when the wind blows), biomass energy comes as an already stored solar energy resource. It can thus be used as needed rather than as available. Although the intermittency of solar and wind energy can be moderated by gathering them over a large geographic region, they still require dispatchable backup power such as can be provided by biomass.

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[6] In the longer term, population growth in developing countries may surpass agricultural productivity growth and increase demand for food imports. Some of this demand may be supplied by the United States. No one knows, however, what the net effect is likely to be.

[7] Scott Kilman, "U.S. Is Steadily Losing Share of World Trade in Grain and Soy beans," *Wall Street Journal, Dec. 3, 1992,* p. A1.

[8] An example is the Conservation Reserve Program (CRP) which pays farmers to take lands out of production of a marketable crop for 10 years in order to protect more erodible or fragile soils with permanent cover.

THE BIOENERGY AGENDA

While bioenergy crops have great potential to help meet a number of pressing problems, the extent to which this potential can be realized will depend on a number of factors. These include:

- Research and development—Relatively little R&D has been done on the environmental impacts of energy crops in the United States. Most studies have been short-term, limited in scope, and confined to small scales. Although careful studies have been conducted at a handful of sites across the United States, the results tend not to be readily transferable to significantly different sites, crops, or management practices. Consequently, most practices in the field, as well as much of the analysis in this report, have been developed by analogy with conventional agricultural or forestry practices. This approach has significant limitations. For example, energy crops can have significantly deeper and heavier rooting patterns than conventional agricultural crops, affecting soil carbon balances, water balances, and agricultural chemical fates. Even less is known about the habitat impacts of energy crops; some of the very first studies are just now underway at a few locations. Virtually all proposed habitat practices are based on ecological theory and by analogy with conventional crops.

  Thus, R&D is needed on soil, water, and air quality issues, and these environmental analyses should be done on a total fuel-cycle basis. R&D is also needed on how to design desirable landscapes at the micro and macro level in order to realize the potential habitat benefits of bioenergy crops, including the relative benefits of buffers and corridors using energy crops—for which almost no R&D has been done to date. Inter-planting multiple species can potentially improve habitat but may complicate energy conversion processes which are typically designed for a narrowly defined input feedstock. Thus, R&D is needed to tailor energy conversion processes to accept a wide variety of mixed feedstocks, particular] y those with special habitat value. Landscape design and conversion processes must also maintain high productivity and reasonable economic returns. Experience gained in Europe and elsewhere in recent years may be useful in addressing these issues.
- Demonstrations-Demonstrations are needed (and should be closely coupled with the above R&D agenda) in order to determine how best to structure energy crops for their environmental (soil, water, air, habitat) value, to determine what their environmental value actually is by field observations, and to establish pilot energy conversion facilities, such as bioenergy to electricity, bioenergy to liquid (transport) fuels such as ethanol or methanol, or bioenergy to other petrochemical substitutes. Such demonstrations are most useful if they are of sufficient scale to clarify the characteristics of a fully functional infrastructure and thus reliably and cost-effectively link the feedstock production activities to the energy conversion processes.
- Commercialization—Farmers cannot afford to grow biomass unless electric power or fuel conversion facilities are in place to purchase it. Conversion facilities cannot be built unless the biomass feedstock is available and an end-use market is ready. An end-use market is difficult to develop without assured supplies of fuel. Infrastructure development may be needed at all these levels. Mechanisms for addressing this “chicken and egg” problem of developing bioenergy production, conversion facilities, and end-use markets are needed. On the biomass production side, this may require addressing issues of farmer risk, flexibility, finances, education and extension, and other issues. Fundamental issues of land use and property rights may also arise in connection with environmental considerations of energy crops. Studies of how best to address these issues might be conducted in parallel with demonstrations.
- **Institutional** Issues—The multiplicity of sectors affected by energy crops—agriculture, energy, environment, forestry, etc.—poses a substantial and, in some ways, unique institu-

tional challenge in developing coherent policy goals, processes, and effective coordination.

Energy crops may help solve some of our national energy and environmental problems. They potentially can provide a modest fraction of our current level of energy needs, perhaps 10 to 30 percent, and they have potential environmental benefits compared with conventional agricultural crops. Energy crops are no substitute, however, for natural habitats on contiguous landscapes; energy cropping should primarily be considered for surplus agricultural and degraded lands. Finally, the regional impacts of energy crops will be mixed. They cannot readily be grown everywhere. They are most likely candidates where agriculture and forestry are already well-established industries.

Within these limits, energy crops show promise to help meet a number of national needs-economic, environmental, budgetary, and national security. The extent to which this potential can be realized will depend on how well the many competing economic/environmental, rural/urban, regional, and other interests can be balanced. This background report is intended to contribute to that national debate.

Introduction 2

Biomass is mankind's oldest energy resource. It has been periodically misused throughout history, sometimes with serious environmental and other consequences. Cyprus provided the bronze needed by the ancient Greeks for weaponry; wood shortages are a likely cause of the reduction in bronze smelting there by 1300 BC which forced rationing on the Greek mainland and weakened the Mycenaens to outside attack. Aristotle and Plato documented the destruction of forests in Greece itself and the resulting environmental degradation. The Remans were forced to import wood from North Africa, France, and Spain to keep their industries, public baths, and military operational. England suffered severe deforestation in many areas during her early industrial period—citizens even rioted over rising wood prices; eventually the transition to coal was made.[1] The United States went through a similar transition among energy resources over the past 150 years (figure 2-1).

Today, a variety of concerns has prompted a new look at biomass as an energy resource. Biomass, in combination with advanced combustion and/or conversion technologies, has the potential to contribute needed energy resources for transport, electric power, and industry. Bioenergy may provide economic benefits to the rural economy and possibly to the Nation. By substituting for imported oil, bioenergy also may provide some national security benefits. These potential economic, budgetary, and security values of bioenergy must be weighed, however,

Today, a variety of concerns has prompted a new look at biomass as an energy resource.

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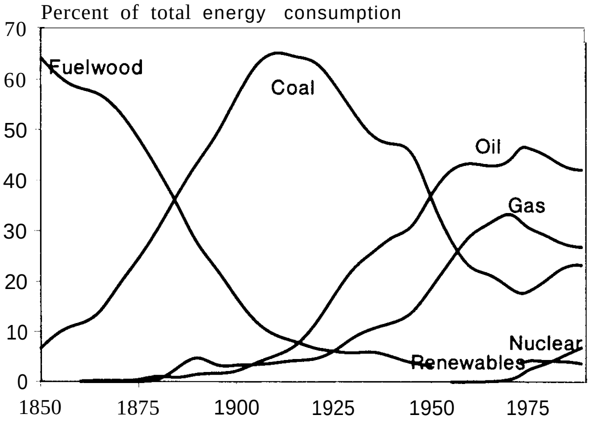
[1] John Perlin and Boromir Jordan, "Running Out—4200 Years of Wood Shortages," *Convolution Quarterly,* Spring 1983, pp. 18-25; Erik P. Eckholm, *Losing Ground: Environmental Stress and World Food Prospects* (New York, NY: W.W. Norton and Company, 1976).

Figure 2-I —U.S. Energy Consumption Patterns from 1850 to 1990



This figure shows the generational shift from one fuel to the next for the United States, from wood in the 1800s to coal by the turn of the century, and then to oil and gas from the 1950s on.

SOURCES: Office of Technology Assessment; J. Alterman, *A Historical Perspective on Changes in U.S. Energy-Output Ratios,* EPRI EA-3997 (Palo Alto, CA: Electric Power Research Institute, June 1985).

stoves. Municipal solid waste and ethanol provide most of the remaining bioenergy (table 2-1).[5]

The Transport Sector

Transportation consumes about one-fourth of total U.S. primary energy use and nearly two-thirds of oil use. Of U.S. oil consumption—which provides 42 percent of the total U.S. energy consumption of about 85 EJ—roughly half is now imported and this share is increasing. With current policies, U.S. imports of oil are likely to increase dramatically over the next several decades (figure 2-3).

Renewable energy resources and technologies—particularly bioenergy-offer the potential to reduce these trends in the longer term. Technologies for biomass feedstock conversion and use in the transport sector are given in box 2-A. Whether or not this potential can be realized, however, remains uncertain and depends on the details of their cost and performance compared against alternative uses of the land and other means of meeting these needs.

THE U.S. ENERGY SECTOR AND BIOENERGY

In the United States,[2] bioenergy accounts for roughly 4 percent of total energy use, or about 3 Exajoules (EJ).[3] Oil, coal, and natural gas contribute 41 percent (35 EJ), 23 percent (20 EJ), and 25 percent (21 EJ) respectively (figure 2-2).[4] The primary uses of bioenergy in the United States are industrial cogeneration, primarily in the pulp and paper industry, and for residential heating by wood

Table 2-1—U.S. Biofuel Production and Use, 1989

Fuel	ExaJoules
Wood	2.6
Industrial	(1.7)
Residential	(0.9)
Utility	(0.01)
Biofuels from waste	0.36
Municipal solid waste combustion	(0.23)
Manufacturing waste	(0.10)
Landfill gas	(0.03)
Ethyl alcohol	0.075
Total	3.04

SOURCE: Energy Information Administration, "Estimates of U.S. Biofuels Consumption 1989," U.S. Department of Energy, Washington, DC, April 1991.

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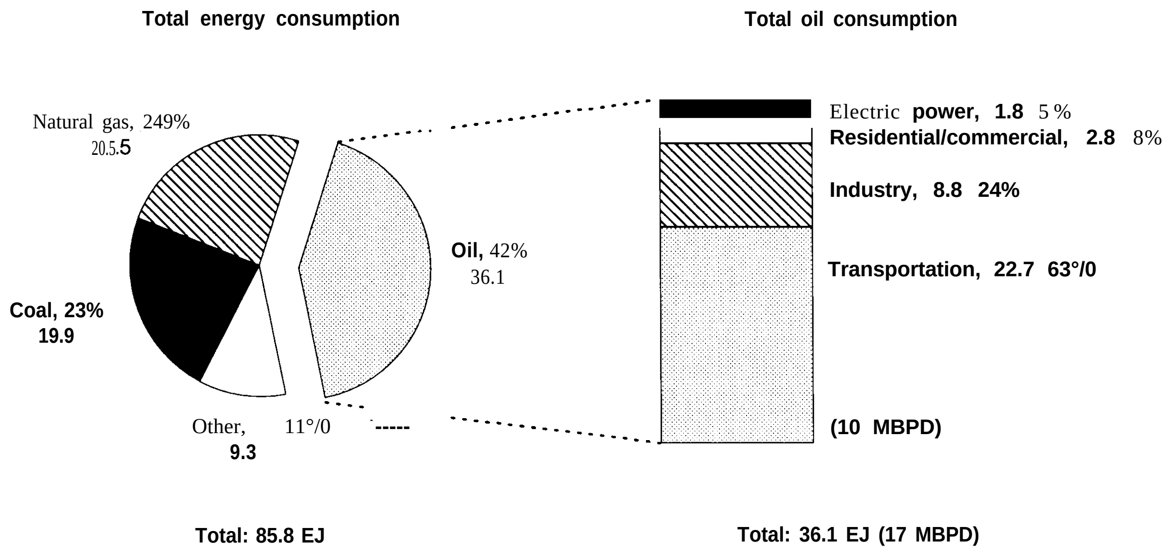
[2] Bioenergy is critical to the economies of developing countries, particularly in rural areas. See, for example: U.S. Congress, Office of Technology Assessment, Energy *in Developing Countries, OTA-E-486* (Washington, DC: U.S. Government Printing Office, January 1991); U.S. Congress, Office of Technology Assessment, *Fueling Development: Energy Technologies for Developing Countries, OTA-E-516* (Washington, DC: U.S. Government Printing Office, April 1992).

[3] See appendix B for units, their definition, and their equivalences.

[4] U.S. Department of Energy, Energy Information Administration, *Annual Energy Review, 1992,* Report No. DOE/EIA-0384(92), June 1993.

[5] For a detailed bibliography, see: United States Department of Agriculture, "Biofuels: January 1986-August 1992," National Agricultural Library Quick Bibliography Series QB 92-63, September 1992.

Figure 2-2—U.S. Energy and Oil Consumption, 1989



This figure shows U.S. energy consumption for oil, coal, natural gas, and others, and breaks oil consumption down by its end use. About 42 percent of U.S. energy consumption is in the form of oil and nearly two-thirds of this oil is used for transport.
SOURCE: Energy Information Administration, *Annual Energy Review* 1992, U.S. Department of Energy, DOE/EIA-0384(92), June 1993.

with alternative fuels and technologies, as well as the larger context of urban design, the development of transport infrastructures, and internalizing the external costs of fossil fuel use and transport generally.[6]

The Electricity Sector

Coal, nuclear, hydro, and natural gas are the principal sources of electricity in the United States. Bioenergy, primarily wood and wood wastes in the forest products industry, is an important fuel for industrial cogeneration. Independent power producers are also turning frequently to bioenergy resources, including wood, municipal wastes, and landfill gas, for power production (table 2-2). More than 8 GW of biomass-fired capacity are now installed in the United States.[7]

Utilities are becoming increasingly interested in biomass as a fuel for power production. Factors contributing to this interest include: improved technologies for burning/gasifying biomass and generating power (see box 2-A);[8] pressure to reduce emissions under the Clean Air Act Amendments of 1990; the 1.5 cent/kWh credit authorized under the Energy Policy Act of 1992 for closed loop biomass systems; and others.

In addition, biomass-fueled electricity generation may play a particularly important role if there is a greater emphasis in the future on using renewable forms of energy. In contrast to intermittent

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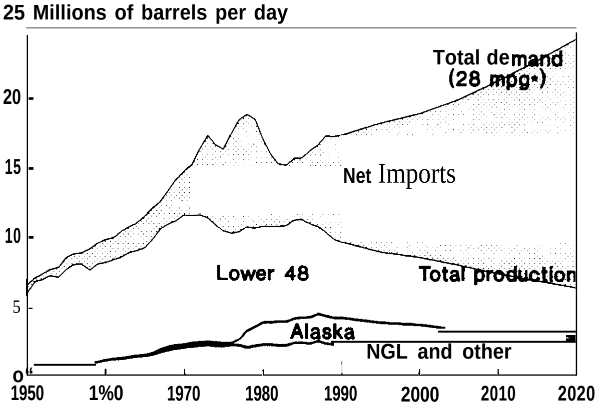
[6] A forthcoming Office of Technology assessment charts a variety of future renewable energy resource and technology paths for transport; analyzes their relative economic, environmental, and technological performance vis a vis conventional fossil-fueled systems; and examines the key RD&D and commercialization issues that must be addressed if their potential is to be realized. Technologies examined include ethanol, methanol, and hydrogen used in internal combustion engines and fuel cell vehicles. Broader issues of urban design, infrastructure development, and the externalities of transport are also reviewed there.

[7] National Wood Energy Association, *National Biomass Facilities Directory,* Arlington, VA, 1990.

[8] Robert H. Williams and Eric D. Larson, "Advanced Gasification-Based Biomass Power Generation," Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams (eds.), *Renewable Energy: Sources for Fuels and Electrcity* (Washington, DC: Island Press, 1993).

Figure 2-3—U.S. Oil and Supply Demand Futures



U.S. domestic oil production is declining, while U.S. oil demand is rising with population and economic growth. Shown here is the projected rise assuming that the new cars and light trucks in the United States have their fuel efficiencies frozen at 1990 levels (28 mpg). “Lower 48” represents oil production in the lower 48 states; “Alaska” is the oil production from Alaska, and NGL and other are Natural Gas Liquids and other sources of liquid fossil fuels.

SOURCE: Office of Technology Assessment. Baselines adapted from Energy Information Administration, *Annual Energy Outlook 7997,* U.S. Department of Energy, DOE/EIA-0383(91), March 1991.

Table 2-2—U.S. Winning Competitive Bidsfor New Capacity, 1984-1992

	Capacity MW
Natural gas	**6,628**
Coal	**1,969**
Refurbishment	**1,127**
Coal wastes	**720**
Oil	**340**
Coke	**165**
Total fossil	*10,949*
Geothermal	**825**
Wood and biomass	**776**
Municipal waste	**564**
Hydro	**125**
Wind	**63**
Landfill gas	**28**
Total other	*2,381*

Note that these include only winners from competitive bidding solicitations. Many other power plants, primarily fossil-fueled, were built outside of competitive bidding solicitations.

SOURCE: *Robertson’s Current Competition, vol. 3, No. 2,* May 1992.

renewable such as solar (available when the sun shines) and wind (available when the wind blows), biomass energy comes as an already stored solar energy resource. It can thus be used as needed rather than as available. Although the intermittancy of solar and wind energy can be moderated by gathering them over a large geographic region, they still require dispatchable backup power such as can be provided by biomass.[9]

The Industrial Sector

The industrial sector uses roughly one-third of primary energy in the United States. Wood as a fuel contributes about 8 percent of total industrial sector primary energy use, mainly in the pulp and paper industry where it contributes as much as three-quarters of energy needs (figure 2-4).[10]

Industry is interested in increasing use of these fuels. For example, the typical pulp and paper operation has three principal waste streams which can provide energy: hog fuel, black liquor, and forest residues. Hog fuel is the bark, sawdust, and other scrap produced in reducing logs to feedstock for the pulping process. Hog fuels could supply about 3 GJ[11] per tonne of pulp produced (GJ/tp). Black liquor, from the chemical pulping process, averages an energy content of about 13 GJ/tp. Other residues are currently left in the forest when harvesting the trees. A portion of these forest residues might be collected, but the long-term impact this would have on forest soils would need to be examined closely (see ch. 3). If fully recovered, the estimated energy content of forest resi-

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[9] Other renewable energy resources that can similarly provide baseload power include geothermal and hydropower.

[10] This is the energy used at the site and does not include energy losses in generation, transmission, and distribution of electricity from offsite to the plant, the refinery losses of converting crude oil to fuel oil and transporting it to the site, or other such offsite losses.

[11] Fifty kilos of dry wood have an energy content of about l gigajoule (GJ).

Box 2-A--Bioenergy Conversion Technologies

Biomass can be **used directly to generate** electricity or it can be converted to a liquid (or gaseous) transportation fuel.

The physical and chemical composition of biomass feedstocks varies widely, potentially requiring the tailoring of particular conversion technologies to specific biofuels (with corresponding negative impacts on habitat if narrowly specified monoculture must be used—-see ch. 3). The relatively low bulk densities of biomass and large required collection areas limit the amount of biomass transported to any given site. This constrains the size of individual conversion facilities and limits the extent to which economies of scale in capita! and other costs can be captured.[1]

Electricity. Virtually all existing biomass electric plants use steam turbine technology and, **due to use of old, Inefficient, and small-scale technologies, their** efficiency tends to be low-l **7 to 23 percent** in California, **for example. in comparison, modem coal plants run** at efficiencies of perhaps 35 percent. Steam turbine technology is fairly mature and few advances are foreseen for biomass. Improvements are possible, however, in biomass handling. Whole-tree energy systems, for example, use the flue **gas for** drying, reduce the required handling, increase net energy efficiencies slightly (in part through a higher pressure steam cycle), and avoid chipping costs.

Of greater potential is to gasify the biomass and use the gas generated to **power a** gas turbine. Gasifiers **and gas turbines** are relatively insensitive to scale and can operate at much higher efficiencies than steam turbines in the range of sizes suitable **for biomass systems.**

In a biomass gasifier/gas turbine system, biomass is gasified in a pressurized air-blown reactor and the products cleaned of particutates and other contaminants before being burned in an efficient power cycle based on gas turbines, such as the steam injected gas turbine (STIG), intercooled STIG (ISTIG), or a combined cycle.[2] Hot gas cleanup avoids cost and efficiency penalties, and pressurized gasification avoids energy losses **associated with compressing** the fuel gas after gasification. It is necessary, however, to **remove** trace amounts of alkali vapor from the gas before it enters the gas turbine. There appears to be a basic understanding of the means for adequately cleaning gases **for gas turbine applications with either fluidized** bed gasifiers[3] or updraft gasifiers, although there has **been no commercial demonstration of alkali removal. A demonstration 6** MWe pressurized fluidized **bed** plant, however, has recently gone on **line in** Sweden.

Biomass gasifier/gasturbines (BIG/GTs) are characterized by high conversion efficiencies and low expected unit capital costs ($/kW) in the **5 to** 100 MWe size range.[4] The upper end of this range is probably near the

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[1] Typical rates of biomass fuel production, or use at individual sites, range up to a maximum of some 300 to 400 MW_{fuel} &4 to 72 dry tonnes per hour) at large factories that produce biomass as a byproduct and use it for energy (e.g., cane sugar and kraft pulp factories). This can be compared with the 800 to 4,000 MW of coal consumed at central station electric power plants. Larger concentrations of biomass could be made available, e.g., from plantations dedicated to producing biomass for energy. Under such schemes, transportation costs and land availability will be limiting factors on the quantity of biomass that can be concentrated at a single site.

[2] See E.D. Larson and R.H. Williams, 'steam-injected Gas Turbines," *ASME Journal* Of *Engineering for Gas Turbines and Power,* vol. 109, 1987, pp. 55-83; R.H. Williams and E.D. Larson, "Expanding Roles for Gas Turbines in Power Generation," *Electricity: Efficient End Use and New Generation Technologies, and Their Planning Implications* (Lund, Sweden: Lund University Press, 1989), pp. 503-53; R.H. Williams and E.D. Larson, "Thermochemical Biomass Gasifier/Gas Turbine Power Generation and Cogeneration," Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams (eds.), *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993).

[3] E. Kurkela, P. Stahlberg, M. Nieminen, and J. Laatikainen, "Removal of Particulate, Alkali, and Trace Metals from Pressurized Fluid-Bed Biomass Gasification Products-Gas Cleanup for Gas Turbine Applications," in Donald L. Klass, *Biomass and Wastes XV* (Chicago, IL: institute of Gas Technology, 1991).

[4] See E.D. Larson and R.H. Williams, "Biomass-Gasifier/Steam-Injected Gas Turbine Cogeneration," *Journal of Engineering for Gas Turbines and Power, vol. 112,* April 1990, pp. 157-63; P. Elliott and R. Booth, "Sustainable Biomass Energy: Selected Paper (London, England: Shell International Petroleum Co., Ltd., December 1990).

practical upper limit on the size of a biomass installation. Capital costs for gasification and gas cleanup may be lower for biomass than for coal due to the lower operating temperatures and greater volatility of biomass.

Transport Fuels. Biomass-derived fuels-methanol, ethanol, biodiesel, and possibly hydrogen--offer an important opportunity to reduce U.S. fossil fuel consumption transport. Of particular interest here are ethanol and methanol

Ethanol. Much of the attention and funding of biomass fuels has been focused on grain-to-ethanol production. In the United States, commercial operations annually produce about 850 million gallons of ethanol from corn by fermentation. This ethanol is blended in a typically 1 to 9 ratio with about 8 percent of U.S. gasoline as an octane enhancer. (Alternatively, minor engine modifications allow ethanol to be used as a full replacement for gasoline.) This production is supported by tax incentives and low prices for alternative uses of the corn crop. Expansion of supplies sufficient to significantly reduce US. oil imports, however, is not realistic if limited to the use of grain; nor would it be economical.

Ethanol's environmental benefits include: a reduction of carbon monoxide when used in blends; possible reductions in urban ozone;[5] and, if produced from biomass on a renewable basis, no or low net contributions of the greenhouse gas carbon dioxide to the atmosphere.

Advanced bioengineering and other technologies are now enabling researchers at the National Renewable Energy Laboratory (NREL), Tennessee Valley Authority, and elsewhere to convert cellulosic feedstocks (e.g., the corn stalk, not just the grain) to ethanol. This greatly increases the potential volume of feedstock that could be converted to ethanol and reduces its cost. Although substantial technical hurdles remain, particularly scale-up of laboratory processes, researchers hope to lower the cost of ethanol to competitive levels with gasoline by the year 2000.

Woody and herbaceous biomass, referred to generally as lignocellulosic materials, consist of three chemically distinct components: cellulose (about 50 percent), hemicellulose (25 percent), and lignin (25 percent).[6] Most proposed ethanol production processes involve separate processing of these components. in the first step, pretreatment, the hemicellulose is broken down by acids or enzymes into its component sugars and separated out.[7] The lignin is also removed. The remaining cellulose is then converted into fermentable glucose through hydrolysis, Following fermentation, the products are distilled to remove the ethanol. Byproducts of the separation process, such as furfural and lignin, can be used as fuel or sold separately.

Methanol, Methanol is a liquid fuel that can be produced from natural gas, coal, or biomass via gasification and catalysis. Methanol does require somewhat greater fuel-system material modifications than ethanol, but flexible-fueled vehicles, which can operate on methanol, ethanol, gasoline, or a mixture of these fuels, are already being produced in limited numbers in the United States.[8] The use of such vehicles could ease the transition away from gasoline.

Biomass-to-methanol plants would typically convert 50 to 60 percent of the energy content of the input biomass into methanol, though some designs have been proposed with somewhat higher conversion efficiencies. Three basic thermochemical processes are involved in methanol production from biomass:[9]

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[5] US. Congress, Office of Technology Assessment, *Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles,* p. 108.

[6] J.D. Wright, "Ethanol from Lignocellulose: An overview,'" *Energy Progress,* vol. 8, No. 2, 1988, pp. 71–78.

[7] C.E. Wyman, N.D. Hinman, and R.L. Bain, "Ethanol and Methanol from Cellulosic Materials," Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams (eds.), Renewable *Energy:* Sources *for Fuels and Electricity* (Washington, DC: island Press, 1993); P.W. Bergeron, J.D. Wright, and C.E. Wyman, "Dilute Acid Hydrolysis of Biomass for Ethanol Production," *Energy from Biomass and Wastes XII* (Chicago, IL: Institute for Gas Technology, 1989), pp. 1277-96; M.M. Bulls, J.R. Watson, R.O. Lambert, J.W. Barrier, "Conversion of Cellulosic Feedstocks to Ethanol and Other Chemicals Using TVA's Dilute Sulfuric Acid Hydrolysis Process," *Energy from Biomass and Wastes XIV* (London, England: Elsevier Applied Science, 1991).

[8] U.S. Congress, Office of Technology Assessment, Replacing Gasoline, OTA-E-364 (Washington, DC: U.S. Government Printing Office, September 1990), p. 25.

[9] C.E. Wyman, N.D. Hinman, and R.L. Bain, "Ethanol and Methanol from Cellulosic Materials," in Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams (eds.), *Renewable Energy; Sources for Fuels and Electricity,* (Washington DC: Island Press, 1993).

- Production of a “synthesis gas” (a close relative of producer gas) via thermochemical gasification, but using oxygen rather than air in order to eliminate dilution of the product gas with nitrogen (in air). Oxygen plants have strong capital cost scale economies, which contributes to most proposed biomass-to-methanol facilities being relatively large (typically 2,000 tonnes/day or more input of dry biomass). Biomass gasifiers designed for methanol production are not commercially available but research and pilot demonstrations are in planning or underway.[10]
- The synthesis gas is cleaned and its chemical composition is adjusted to produce a gas consisting purely of hydrogen (H_2) and carbon monoxide (CO) in a molar ratio of 2:1. The specific equipment configuration in the second step in methanol production will vary depending on the gasifier **used, A reactor common to all systems is a “shift”; reactor** used to achieve the desired 2:1 ratio of H_2 to CO by reacting steam with the synthesis gas. **The** shift reactor is a commercially established technology.
- . •**The** gas is compressed and passed through a pressurized catalytic reactor that converts the CO and H_2 into liquid methanol. A variety of commercial processes can be used.

Tests of methanol’s potential to reduce air pollution have yielded mixed results.[11] Potential greenhouse gas benefits of methanol depend on the feedstock: renewably produced biomass feedstocks would make little or no net contribution to greenhouse gas emissions; fossil fuel feedstocks would increase them for coal and decrease them for natural gas. Methanol does have some environmental disadvantages, particularly greater emissions of formaldehyde, which could require special emission controls. Today’s production vehicles, however, are certified as meeting California’s formaldehyde emissions standards.[12]

10&3@ A.A.C.M. Beenackers and W.P.M. van Swaaij, “The Biomass to Synthesis *Gas* Pilot Plant Programme of the CEC: A First Evaluation of Results,” *Energy from Biomass, 3rd EC Conference* (Essex, United Kingdom: Elsevier Applied Science, 1985), pp. 120-45; E. C), Larson, P. Svenningsson, and L Bjerle, “Biomass Gasification for Gas Turbine Power Generation,” *Electricity: Efficient End-Use and New Generation* Technologies, *and their Planning Implications* (Lund, Sweden: Lund University Press, 1989), pp. *697-739;* R.J. Evans, R.A. Knight, et al., *Development of Biomass Gasification to Produce Substitute Fuels,* PNL-6518 (Richland, WA: Battelle Pacific Northwest Laboratory, 1988); Chem Systems, “Assessment of Cost of Production of Methanol from Biomass,” draft (Golden, CO: Solar Energy Research Institute, December 1989).

[11] U.S. Congress, Office of Technology Assessment, Replacing Gasoline, OTA-E-364 (Washington, DC: U.S. Government Printing Office, September *1990).*

[12] Roberta Nichols, Ford Motor Company, J) rsonal communication, Sept. 1, 1993.

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dues would be about 25 GJ/tp. Combined, these energy resources total some 41 GJ/tp.[12]

Most kraft pulp mills current] y use black liquor for cogenerating steam and electricity onsite. High-efficiency steam-injected gas turbines, combined cycles, or other high-performance generation technologies might be able to generate as much as 4000 kWh of electricity per ton of pulp produced if all of the hog fuel, black liquor, and recoverable forest residues were used. After meeting onsite needs,[13] this would leave a substantial amount of power—worth nearly half the value of the pulp-that could be sold to the grid.[14]

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[12] Eric D. Larson, “Prospects for Biomass-Gasifier Gas Turbine Cogeneration in the Forest Products Industry: A Scoping Study,” Center for Energy and Environmental Studies Working Paper No. 113, (Princeton, NJ: Princeton University, February 1990).

[13] Onsite needs today are typically about 740 kWh/tp of electricity plus some 4,300 kg/tp Of Steam, with the potential for significant reductions.

[14] Assuming $0.07/kWh. See: Eric D. Larson, “Biomass-Gasifier/Gas-Turbine Applications in the Pulp and Paper Industry: An Initial Strategy for Reducing Electric Utility CO_2 Emissions,” Conference on Biomass For Utility Applications, Electric Power Research Institute, Tampa, FL, Oct. 23–25, 1990; Eric D. Larson, “Prospects for Biomass-Gasifier Gas Turbine Cogeneration in the Forest Products Industry: A Scoping Study,” Center for Energy and Environmental Studies Working Paper No. 113, (Princeton, NJ: Princeton University, February 1990).

The Residential Sector

The residential/commercial sector accounts for about one-fifth of total primary energy use, with electricity and natural gas the primary fuels used. Wood fills roughly 10 percent of the space heating requirements, or roughly 5 percent of the total energy used in the residential sector.[15] Prospects for substantially increasing wood use in this sector are not promising because of the relatively high level of emissions generated by small household wood stoves, and the difficult and expensive logistics of delivering wood fuels to highly dispersed small users.

Impacts of U.S. Energy Demand Patterns and Bioenergy

Current U.S. energy demand patterns affect the economy, national security, and the environment (see ch. 3). Bioenergy could reduce these impacts, but by itself cannot eliminate them. Its relative value in meeting these needs will have to be compared with other potential uses for the land, alternative fuels and technologies, and other approaches.

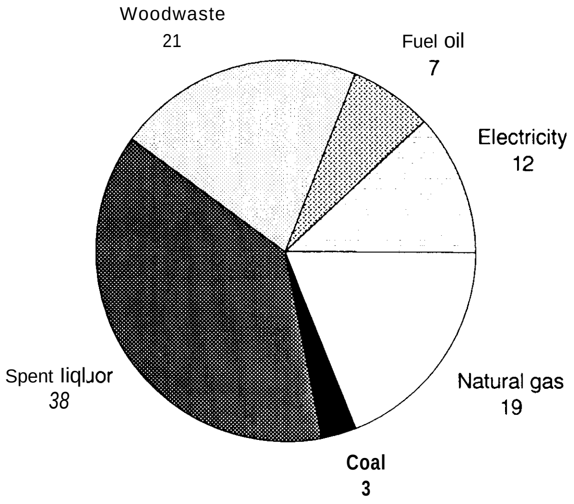
U.S. expenditures on foreign oil are currently running about $50 billion per year and are destined to increase sharply as U.S. oil production continues its decline. Several U.S. electric utilities are also now importing low sulfur coal.[16]

The economic impacts of these imports are hard to assess as they depend on: the manner in which these petrodollars are recycled back into the U.S. economy; changes in the terms of trade; employment in U.S. export industries; and other factors.[17] These economic impacts are also spread unevenly within the United States.

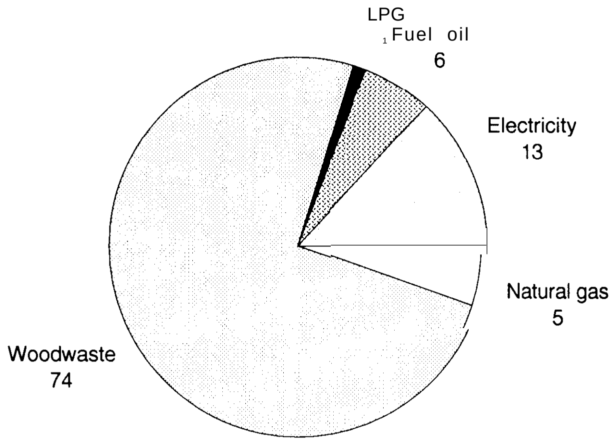
The ready availability of cost-effective and high-performance alternative fuels and technolo-

Figure 2-4-Energy Sources Used by the Wood and Paper Products industries

Paper products industries



Wood products industries



This figure shows the extensive use of biomass fuels—woodwaste and spent liquor—in the wood and paper products industries. Of total end-use energy consumed, 60 to 75 percent is provided by biomass.
SOURCE: Energy Information Administration, *Estimates of U.S. Bio-fue/s Consumption 1989,* U.S. Department of Energy, April 1991.

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[15] U.S. Department of Energy, Energy Information Administration, "Estimates of U.S. Biofuels Consumption 1989," Report No. SR/CNEAR-91-02, Washington, DC, April 1991.

[16] Jane Turnbull, Electric power Research Institute, personal communication, Sept. 1, 1993.

[17] H.G. Broadman, "The Social Cost of Imported Oil," *Energy Policy, vol.* 14, *1986,* pp. *242–52;* H.G. Broadman and W.W. Hogan, "IS An Oil Tariff Justified? An American Debate: The Numbers Say Yes," *Energy Journal, vol. 9, No. 3, 1988,* pp. *7–29;* M. Ethridge, "The Social Costs of Incremental Oil Imports: A Survey and Critique of Present Estimates," Discussion Paper #25, American Petroleum Institute, Washington, DC, February 1982; Daniel Sperling and Mark A. DeLuchi, "Transportation Energy Futures," *Annual Review @Energy,* vol. 14, 1989, pp. 375-424.

gies could help reduce oil price volatility, oil price increases, and oil import costs. In addition, they would reduce the uncertainty and risk associated with price volatility and thus might help reduce the corresponding distortion of investment decisions toward the short term. Fuels derived from biomass feedstocks might provide some of these alternatives.

Reliance on imported oil also poses national security risks. These can be quickly enumerated but defy quantification. Such risks include: future involvement in Middle East or other conflicts; possible pressure on U.S. alliances; economic impacts due to a sudden oil curtailment; and many others. The likelihood and severity of these impacts will depend on the extent to which potential anti-Western factions might gain control of key oil-exporting countries and exercise this power, the discovery and development of oil resources outside the Middle East, improvements in secondary oil recovery from existing fields, and the development of alternative transport fuels and technologies.[18]

THE RURAL ECONOMY AND BIOENERGY[19]

Rural economies in the United States have been hard pressed for many years. Between about 1980 and 1990, the U.S. share of the world's total agricultural trade dropped from 28 to 21 percent. At the same time, the European share grew from about 13 to 19 percent. China is now the world's second largest corn exporter and Brazil is a major exporter of soybeans. Roughly half of the ship-loading grain terminals in the United States are reportedly closed, about to close, or for sale.[20] Due to these pressures, there is a growing need to find alternative crops for rural agricultural communities: to provide employment, to stabilize rural incomes, and to maintain the rural infrastructure of equipment and supplies distribution and service. Bioenergy crops might serve such a role if mechanisms can be found to overcome a variety of market and institutional obstacles to their use.

The rural economy faces several trends; bioenergy may be able to moderate some of their impacts. Demand for conventional agricultural products is likely to grow slowly: U.S. population growth is low[21] and the U.S. consumer is reasonably well fed. At the same time, foreign demand is uncertain.[22] It may be met in the future by new export powerhouses, particularly eastern Europe and the former Soviet Union, Latin America, and elsewhere.[23] Efforts in those regions will be strongly aided by adoption of the modern agricultural techniques and crop varieties pioneered by the United States; thus, U.S. farmers are not

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[18] U.S. Congress, Office of Technology Assessment, *U.S. Vulnerability to an Oil Import Curtailment: The Oil Replacement Capability,* OTA-E-243 (Washington, DC: U.S. Government Printing Office, September 1984); U.S. Congress, Office of Technology Assessment, *U.S. Vulnerability to an Oil Import Curtailment: The Technical Replacement Capability,* OTA-E-503 (Washington, DC: U.S. Government Printing Office, October 1991).

[19] For broader reviews of the economic impacts of bioenergy crops, see Southeastern Regional Biomass Energy Program, Tennessee Valley Authority and Meridian Corporation, "Economic Impact of Industrial Wood Energy Use in the Southeast Region of the U.S.," four volumes, Muscle Shoals, AL, and Alexandria, VA, November 1990; J.W. Onstad, M.S. Lambrides, B.S. McKenna, "Analysis of the Financial and Investment Requirements for the Scale-Up of Biomass Energy Crops," National Renewable Energy Laboratory and Meridian Corporation, Alexandria, VA, September 1992; Ed Wood and Jack Whittier, "Biofuels and Job Creation: Keeping Energy Expenditures Local Can Have Very Positive Economic impacts," *Biologue,* vol. 10, No. 3, September/December 1992, pp. 6-11; Meridian Corporation and Antares Group Inc., "Economic Benefits of Biomass Power Production in the U.S.," *Biologue,* vol. 10, No. 3, September/December 1992, pp. 12-18; R.L. Graham, B.C. English, R.R. Alexander, M.G. Bhat, "Biomass Fuel Costs Predicted for East Tennessee Power Plant," *Biologue, vol. 10, No. 3,* September/December 1992, pp. 23–29; "Electricity from Biomass: A Development Strategy," Solar Thermal and Biomass Power Division, Office of Solar Energy Conversion, U.S. Department of Energy, DOIYCH1OO93-152, April 1992.

[20] Scott Kilman, "U.S. Is Steadily Losing Share of World Trade in Grain and soy beans," *Wall Street Journal,* Dec. 3, 1992, p. Al.

[21] U.S. population growth is one of the highest of the industrial countries, however.

[22] In the longer term, Population growth in developing countries may surpass agricultural productivity growth and increase demand for food imports. Some of this demand may be supplied by the United States. No one knows, however, what the net effect is likely to be.

[23] Of course, this will require heavy investment to develop the needed infrastructure of farming equipment, roads, storage facilities, and shipping terminals. Such investment capital is now very limited in these countries.

assured of a continuing comparative advantage, at least not of the magnitude they have enjoyed in the past.

The trend to farming as an agribusiness is likely to continue as well. This will be an inevitable result of the need to maintain some competitive advantage, and will require increased use of modern chemistry, biology, computer, and telecommunication technologies, creating a production unit with sophisticated stocks and flows of goods and services.[24]

Environmental considerations are likely to play an increasing role in farming practice as well. Indirectly, increasing attention to environmental considerations on public lands may push fiber and other production activities toward private and marginal lands. At the same time, increasing attention to environmental issues on private lands may also have an impact on cropping practices,

Energy crops may provide alternative sources of income and help diversify risk for the farmer. Energy crops have the potential to redirect large financial flows from foreign oil or other fossil energy resources to the rural economy, while simultaneously reducing Federal agricultural expenditures. Realizing this potential, however, will require further development of economically and environmentally sound energy crops, their successful commercialization, and carefully crafted policies to make the transition to energy crops without injuring the farm sector or exposing it to undue risk. It will also depend on the relative value of other uses of this land and the costs and benefits of other fuels and technologies.

Federal agricultural expenditures play a noted role in the rural economy. The Federal budget is under great pressure, however, and agricultural programs—like everything else—are under increased scrutiny for savings. Currently, Federal programs to prevent soil erosion (see box 2-B) and various commodity support programs to strengthen crop prices together cost roughly $10

Box 2-B-Conservation Compliance Programs

Conservation compliance was enacted under the 1985 Food Security Act, as amended in 1990, in which all farmers cultivating highly erodible land must fully implement an approved conservation plan by 1995 or risk losing certain farm benefit programs. At the same time, the Conservation Reserve Program (CRP) pays farmers with highly erodible or otherwise environmentally fragile or sensitive land to take it out of production under 10-year contracts. At present, some 15 million hectares are enrolled in CRP, with annual payments averaging roughly $110 per hectare. At the end of the contract, land that is highly erodible must meet conservation compliance conditions.

Failure to comply with the conservation plan results in the potential loss of a variety of benefits, including: eligibility for price supports and related programs; farm storage facility loans; crop insurance; disaster payments; storage payments; any Farmers Home Administration loans that will contribute to erosion on highly erodible lands; and several other types of assistance.

Conservation compliance affects some 55 million hectares, more than one-third of U.S. cropland. A key aspect of about three-quarters of the conservation compliance plans to date is the use of agricultural residues to control erosion. Use of such residues for energy may then conflict with soil erosion concerns (see ch. 3).

For more information, see Jeffrey A. Zinn, "Conservation Compliance: Status and Issues," Congressional Research Service, 93-252 ENR, Feb. 24, 1993.

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[24] U.S. Congress, Office of Technology Assessment, *A New Technological Era for American Agriculture*, OTA-F-474 (Washington, DC: U.S. Government Printing Office, August 1992); William E. Easterling, "Adapting United States Agriculture to Climate Change," contractor report prepared for the Office of Technology Assessment, February 1992.

billion per year. Bioenergy crops are a potential alternative cash crop that could protect fragile soils or could be grown on lands previously idled in order to strengthen commodity crop prices. Earnings from the energy crop might then allow Federal supports to be eased while maintaining farm income. Of course, the relative environmental benefits of energy crops versus current soil conservation programs such as the Conservation Reserve Program would again depend on the specific energy crops grown and how the land was managed. The relative economic and budgetary value of producing bioenergy crops would have to be compared with potential alternative uses of the land. Designing Federal programs to achieve such ends while minimizing disruption and risk to farmers also presents challenges.

BIOENERGY RESOURCES

Biofuels currently provide about 3 EJ, or 4 percent of U.S. primary energy. Some researchers estimate that biofuels have the potential to provide 15 EJ of energy annually by 2010 and perhaps 25 EJ by 2030.[25] Recent detailed econometric studies estimate that the agricultural sector could support the production of roughly 10 EJ of delivered ethanol from cellulosic biomass (not from grain, sugar cane, etc.) by the year 2030 with net benefits to the agricultural economy.[26] Projections based on a business-as-usual estimate nonliquid biomass fuels will provide 4-8 EJ in 2030.[27] These projections will not be critiqued here. Instead, the focus of this report is to examine the environmental implications if such large land areas are converted to energy crops.

Three sets of biomass resources could be used: municipal solid wastes (MSW); agricultural and forestry residues; and bioenergy crops. Each of these resources has unique characteristics and considerations, and differing quantities of material available at a particular price.

Municipal Solid Wastes

Generation of heat or electricity from MSW can be technically difficult under some circumstances due to the variety of materials handled and the need to control emissions of the numerous toxic trace materials found in MSW. Nevertheless, more than 70 waste-to-energy plants are in operation or under construction and roughly 50 are in an advanced stage of planning. By one estimate, U.S. MSW could provide the energy equivalent of more than 10 GW on a continuous basis.[28] Recycling, the slow economy, and other factors, however, have reduced the availability of MSW for some incinerators, increasing costs above those originally projected.[29] In other areas, landfills are filling rapidly yet new sites are controversial, making the prospects for use of MSW brighter.[30] MSW is not considered further in this report.

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[25] J. W Ranney and J.H. Cushman, "Energy from Biomass, " Ruth Howes and Anthony Fainberg (eds.), *The Energy Sourcebook: A Guide to Technology, Resources, and Policy,* (New York, NY: American Institute of Physics, 1991); another set of estimates is given in Solar Energy Research Institute et al., *The Potential of Renewable Energy: An Interlaboratory White Paper, SERUTP-260-3674,* March 1990 (now known as the National Renewable Energy Laboratory).

[26] Randall A. Reese, Satheesh V. Aradhyula, Jason F. Shogren, and K. Shaine Tyson, "Herbaceous Biomass Feedstock Production: The Economic Potential and Impacts on U.S. Agriculture," *Energy Policy,* July 1993, pp. 726-734,

[27] Resource Modeling and Technology Economics Group, "Projections of Wood Energy Use In the United States" (Oak Ridge, TN: Oak Ridge National Laboratory, July 2, 1990, draft).

[28] R.E. Barrett et al., "Municipal Waste-To-Energy Technology Assessment," EPRI TR-1OO58 (Palo Alto, CA: Electric Power Research Institute, January 1992).

[29] Jeff Bailey, "Fading Garbage Crisis Leaves Incinerators Competing for Trash," *Wall Street Journal,* Aug. 11, 1993, p. A1; and Jeff Bailey, "Poor Economics and Trash Shortage Force Incineration Industry Changes," *Wall Street Journal,* Aug. 11, 1993, p. A2.

[30] See, for example, U.S. Congress, Office of Technology Assessment, *Facing America's Trash: What Next for Municipal Solid Waste?* OTA-O-424 (Washington, DC: U.S. Government Printing Office, October 1989); R.E. Barrett et al., "Municipal Waste-To-Energy Technology Assessment," EPR1 TR-1OO58 (Palo Alto, CA: Electric Power Research Institute, January 1992); D. Longwell et al., "Waste-to-Energy Permitting Sourcebook," EPRI TR-1OO7I6 (Palo Alto, CA: Electric Power Research Institute, October 1992); Marjorie J. Clarke, Maarten de Kadt, and David Saphire, "Burning Garbage in the U. S.: Practice vs. State of the Art" (New York, NY: INFORM, Inc., 1991).

Agricultural and Forestry Residues

As with MSW, agricultural and forestry residues can often be obtained at low or no cost: they may have already been trucked to a central processing site such as a sugar mill or sawmill and are available in large quantities. Burning them onsite usually costs less than hauling them away for disposal. More of this resource might be collected and used for energy production,[31] and more efficient energy conversion systems could be used. Residues are an important part of the forest ecosystem, however, and must be carefully guarded from overuse or misuse (see chapter 3).[32]

Energy Crops

Energy crops can be divided into three broad categories: annual row crops such as corn, herbaceous perennial grasses (herbaceous energy crops—HECs) such as switchgrass, and short-rotation woody crops (SRWCs) such as poplar.

Annual row (energy) crops are grown in essentially the same manner as their food crop counterparts and consequently offer few or no environmental benefits over conventional agricultural practices. Because of this, annual row crops are not examined further in this report.

Crops (often annual row crops) have also been used to produce starches, sugars, oils, and other specialty plant products as energy feedstocks. On a national basis, however, their energy production potential is much lower and their costs higher than for cellulosic bioenergy crops (HECs and SRWCs). Consequently, they are not considered further in this report either.

HECs are analogous to growing hay, harvesting the crop instead for energy. SRWCs typically consist of plantations of closely spaced (2 to 3 meters apart on a grid) trees that are harvested on a cycle of 3–10 years. Following harvest, HECs regrow from the remaining stubble and SRWCs regrow from the remaining stumps. Such harvests may continue for 15 to 20 years or more without replanting (fertilizer and other inputs, and maintenance may be required annually, however).

These crops can be planted in a variety of configurations with each other and with agricultural crops to maximize their economic and environmental benefits. Five key variables govern the viability of woody and herbaceous energy crops: technical feasibility; availability of suitable land; economic viability; implementation; and environmental impacts. The first three are described briefly below and implementation issues are described briefly in ch. 4. The potential environmental impacts are examined in detail in ch. 3.

Technical Feasibility

Research and development on plant species and methods of planting have greatly enhanced the technical feasibility of energy cropping. One of the most important technical characteristics of energy crops is their ability to perform well in varying environments. Some energy crops, such as switchgrass and sweetgum, are no more site-specific than a conventional agricultural crop such as corn. Others can be extremely site-specific if very high yields are to be realized. In some cases, species that respond well under research conditions may not do well under actual site conditions during operational trials.[33]

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[31] It may also be possible to increase forest productivity, allowing additional biomass to be extracted, For example, modest applications of nitrogen and phosphorus increased incremental growth severalfold in Scandinavian forests. See, for example, Sune Linder, "The Relationship Between Nutrition and Biomass Production in Swedish Coniferous Stands," Department of Ecology and Environmental Research, Swedish University of Agricultural Sciences, Uppsala, Sweden, no date.

[32] More intensive use of forests for energy may be controversial, however, and use of public lands for biomass energy supply could be strongly opposed by the environmental community. James H. Cook, National Audubon Society, personal communication, Aug. 26, 1993.

[33] A number of factors contribute to this change in response. The new site may be substantially different than the test plot, and conditions may vary across the site itself. These include differences with respect to soil quality, the availability of nutrients and moisture, the presence of weed competitors or of pests and disease, and others. This ha.. implications for the selection of plants, the management of stands, the areas planted, and the regional distribution of plantings. Jack Ranney, Oak Ridge National Laboratory, personal communication, Sept. 1, 1993.

Other desirable characteristics of cellulosic energy crops include fast growth; efficient use of nutrients and water; high density (of wood—high heat value per unit of volume); robustness (ability to withstand weather, pests, and disease); nitrogen-fixing capability (a trait that reduces the need for fertilizer); and good potential for regrowth from stubble (HECs) or stumps (SRWCs). Since the 1970s the USDOE and USDA Forest Service have supported research and development of SRWCs that incorporate most of these features.[34]

Bioengineering eventually may further improve energy crops, such as by increasing productivity or reducing vulnerability to pests and environmental stress. Desirable characteristics, such as nitrogen fixation and fast growth,also may be enhanced through bioengineering. Bioengineering technologies that have proven successful in some cases are cloning and hybridization.[35] For example, USDOE supported research has produced hybrid black cottonwoods that have yields that exceed those of the parent stock by a factor of 1.5 to 2.[36] Genetic engineering of trees is a relatively new field compared with agricultural biotechnology. Technology transfer from agriculture will speed SRWCs genetic engineering, but only to a point; trees and shrubs have unique characteristics, including long generation times. Nonetheless, the potential to increase yields through biotechnology is enormous—according **to** one researcher, even more significant than the successes already achieved in agricultural genetic engineering.[37]

Suitable trials and controls, however, will be needed to ensure that these engineered cultivars do not injure people, animals, or plants directly or injure them indirectly by becoming a weed to agriculture or more invasive of natural habitats than unmodified cultivars. They must also not transfer their genes (e.g., via pollination) to wild relatives whose offspring might become more injurious, weedy, or invasive. Current USDA guidelines require evidence[38] that transgenic crops pose no greater risk to the environment than unmodified plants from which they were derived.[39]

Availability of Suitable **Land**

To be reliable and substantial sources of energy, energy crops will require significant amounts of land.[40] Estimates of the area available for growing energy crops in the United States vary widely, depending on the underlying assumptions about the types of land to be considered, possible alternative uses for the land, the likely demand for food or other exports, the projected increases in agricultural productivity, economic constraints, environmental constraints, the time frame considered, and many others. Estimated areas potentially available for energy cropping range from roughly 15 to 100 million hectares.[41] At yields

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[34] David Dawson, Forest Policy Consultant, personal communication, Aug. 18, 1993.

[35] Edwin H. White et al., "Bioenergy Plantations in Northeastern North America," paper presented at the Conference Energy from Biomass and Wastes XV, Washington, DC, Mar. 25, 1991, p. 10.

[36] Philip A. Abelson, "Improved Yields of Biomass," *Science, vol. 252, No. 5012,* **June 14, 1991, p. 1469.**

[37] Edward A. Hansen, "SRIC Yields: A Look to the Future," *Biomass and Bioenergy,* vol. 1, 1991.

[38] There is debate about *how* good the evidence is or should be.

[39] Peter Kareiva, "Transgenic Plants on Trial," *Nature, VOL 363,* June 17, 1993, pp. *580-581;* M.J. Crawley et al., "Ecology of Transgenic Oilseed Rape in Natural Habitats," *Nature,* vol. 363, June 17, 1993, pp. 620423.

[40] J Warren Ranney et al., "Hardwood *Energy* Crops: The Technology of Intensive Culture," *Journal of Forestry,* vol. 85, pp. 17–28.

[41] K.K. Shaine Tyson, "Biomass Resource Potential of the United States," National Renewable Energy Laboratory, October 1990, draft; James L. Easterly, "Overview of Biomass and Waste Fuel Resources," Strategic Benefits of Biomass and Waste Fuels Conference, Washington, DC, Mar. 30, 1993; W. Fulkerson et al., "Energy Technology R&D: What Could Make a Difference? Volume 2, Supply Technology," ORNL-6541/V2/P2 (Oak Ridge, TN: Oak Ridge National Laboratory, December 1989); D.O. Hail, H.E. Mynick, and R.H. Williams, "Alternative Roles for Biomass in Coping with Greenhouse Warming," *Science and Global Security, vol. 2,1991,* pp. 113-151; James H. Cook, Jan Beyea, Kathleen H. Keeler, "Potential Impacts of Biomass Production in the United States on Biological Diversity," *Annual Review of Energy and Environment, vol. 16,* pp. 401-431, 1991; Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, Robert H. Williams (eds.), *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993).

of 15–20 tonnes/ha, roughly 8 EJ or 10 percent of current U.S. energy demand could be produced on 30 million ha. Some studies estimate the total bioenergy potential as 15 EJ annually by 2010 and perhaps 25 EJ by 2030.@ Recent econometric studies estimate that the agricultural sector could support the production of roughly 10 EJ of delivered ethanol from cellulosic biomass (not from grain, sugar cane, etc.) by the year 2030 with net benefits to the agricultural economy.[43] Projections based on business-as-usual estimate nonliquid biomass fuels will provide 4-8 EJ in 2030.[44]

These estimates of perhaps 8–25 EJ of bioenergy are roughly 10-30 percent of current U.S. energy use of 85 EJ-of which roughly 20 EJ each is for coal in the power sector and for oil in the transport sector. Thus, bioenergy crops can potentially contribute a significant fraction of U.S. energy needs.

To the extent that large areas of land are cultivated for energy crops, however, concerns are raised about the potential environmental impacts on soil quality and erosion, water use, agricultural chemical use, and habitat. These are explored in the following chapter.

Economic viability

Overall, agricultural residues and wood wastes are available in limited supplies for roughly $0.50-$1.50/GJ.[45] Gathering additional residues would raise these costs. The best energy crop sites can now produce perhaps 15-20 tonnes/year at costs in the range of $2 to $4 per GJ.[46] Conversion of these biomass feedstocks to useful fuels raises these costs. In comparison, crude oil at $20 per barrel is equivalent to $3.30/GJ; coal at the current price to electric utilities of roughly $30/ton is equivalent to roughly $1 .50/GJ.[47]

Even if they are not strictly cost effective compared with fossil fuels, energy crops may still be desirable if other benefits-such as environmental advantages, offsets of oil imports, or financial returns to the rural economy—justify the costs.

CLOSE

Concern over the environmental impacts of fossil fuel use, the rural economy, oil import bills and national security, Federal budget deficits, and other factors have prompted many to take a second look at biomass as an energy resource. Although some initially proposed that biomass be used to store (sequester) carbon released by the burning of fossil fuels; more recently many groups have explored the potential of biomass to substitute for fossil fuels.[48] Technological advances in biomass growth, harvesting, transport, and combustion are lowering costs to where plantation-grown biomass

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[42] J.W. Ranney and J.H. Cushman, "Energy from Biomass," Ruth Howes and Anthony Fainberg (eds.), *The Energy Sourcebook: A Guide to Technology, Resources, and Policy, (New* York, NY: American Institute of Physics, 1991). Another set of estimates is given in Solar Energy Research Institute et al., *The Potential of Renewable Energy: An Interlaboratory White Paper, SERlJTP-260-3674,* March 1990; see also the references listed in footnote no. 43.

[43] Randall A. Reese, Satheesh V. Aradhyula, Jason F. Shogren, and K. Shaine Tyson, "Herbaceous Biomass Feedstock Production: The Economic Potential and Impacts on U.S. Agriculture," *Energy Policy,* July 1993, pp. 726-734.

[44] Resource Modeling and Technology Economics Group, "Projections of Wood Energy Use In the United States" (Oak Ridge, ‘N: Oak Ridge National Laboratory, July 2, 1990, draft).

[45] U.S. Department of Energy, "Electricity from Biomass: A Development Strategy," DOE/CH10093-152, April 1992.

[46] J.W. Ranney and J.H. Cushman, "Energy From Biomass," Ruth Howes and Anthony Fainberg (eds.), *The Energy Sourcebook: A Guide to Technology, Resources, and Policy (New* York, NY: American Institute of Physics, 1991); U.S. Department of Energy, "Electricity from Biomass: A Development Strategy," DOE/CH10093-152, April 1992.

[47] U.S. Department of Energy, Energy Information Administration, *Annual Energy* Review *1992,* DOE/EIA-0384(92), June 1993.

[48] See, for example: Solar Energy Research Institute et al., *The Potential of Renewable Energy: An Interlaboratory White paper, SERVTP-260-3674,* March 1990; Office of Conservation and Renewable Energy, U.S. Department of Energy, *Renewable Energy Technology Evolution Rationales,* draft, Oct. 5, 1990; U.S. Environmental Protection Agency, *Renewable Electric Generation: An Assessment of Air Pollution Prevention Potential, EPA/400/R-92/005,* March 1992; Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, Robert H. Williams (eds.), *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993).

may soon be competitive. As the potential scale of use of biomass energy has become apparent, however, environmental concerns have been raised and have begun to be addressed through several efforts.[49] The potential environmental impacts of large-scale bioenergy production is the primary focus of the following chapter.

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[49] This includes "Toward biological Guidelines for Large-Scale Biomass Energy Development," Report of a Workshop Convened by the National Audubon Society and Princeton University, May 6, 1991; and the National Biofuels Roundtable, convened by the Electric Power Research Institute and the National Audubon Society.

Potential Environmental Impacts

3

Bioenergy crops may have a wide range of effects on soils, water, air, habitat, and greenhouse gas emissions. The net effect will depend on the particular type of energy crop and the previous use of the land, the cultivation methods practiced, the overall effort to integrate the crop with the regional landscape ecology, and other factors. The positive environmental impacts of energy crops range from modest to significant compared with most conventional agricultural crops under good management practice; the negative impacts are generally less than those of conventional row crops under typical management. Letting idled or reserve cropland revert back to natural forest or prairie may in the longer term provide equal and usually greater environmental benefits than energy cropping, particularly in terms of habitat, but the risk of global warming and consequent habitat loss may substantially offset these benefits and encourage further consideration of energy crops.

The risk of global warming and consequent habitat loss may. . . encourage further consideration of energy crops.

Substituting energy crops (such as short-rotation woody crops or herbaceous perennials like switchgrass) for conventional row crops (such as corn or soybeans) will under proper management generally improve soil quality, reduce soil erosion and runoff, reduce the use of agricultural chemicals (fertilizers, pesticides, herbicides, fungicides), improve local air quality, and improve habitat for a variety of animals. On the other hand, substituting energy crops for hay, pasture, or well-managed Conservation Reserve Program Lands will generally have mixed impacts.

These projections of the potential environmental impacts of energy crops are based primarily by analog with conventional crops; there is as yet little data for actual energy crops in the field and these data are usually for small field trials collected over short periods rather than large-scale trials over long periods.

Only current, idled, or former croplands, or degraded lands are examined here for potential conversion to energy crops; natural[1] forest, prairie, and wetlands are not considered here as the analysis is beyond the scope of this paper and the potential habitat and other environmental impacts are more likely to be substantially negative.

INTRODUCTION

A wide variety of energy crops is under development (figure 3-1). These include short-rotation woody crops such as hybrid poplars, black locust, silver maple, sweetgum, and eucalyptus; and herbaceous perennials such as switchgrass and reed canary grass.

Energy crops can be considered to be a less intensive form of agriculture. The energy crops considered here are perennials (herbaceous perennial grasses or short-rotation woody crops) and thus require less cultivation than conventional crops. These energy crops also have the potential to be more efficient in the use of fertilizers (i.e., there is some nutrient retention and cycling between growing years that does not occur with annual crops). Overall, the inputs required by energy crops are generally less than for conventional agriculture for several reasons. They often have heavier and deeper rooting patterns, allowing the soil to be utilized to a greater depth for water and soil nutrients, and providing more time to intercept fertilizers or other agricultural chemicals as they migrate downward through the soil. This can also give energy crops greater capacity to intercept fertilizers or other agricultural chemicals in lateral flows from adjacent areas. Heavier rooting puts more carbon into the soil and so assists in creating more productive soil conditions such as enabling the slow continuous release of nutrients or the binding of chemicals so that they are not leached. Finally, energy crops are selected on the basis of their production of cellulosic biomass, which consumes less input energy (light, etc.) per unit of energy stored than for many specialty plant components.

Each of these crops will have different management regimens and differing impacts on soil, water, air, and habitat quality. These issues will be examined broadly here; detailed analysis of specific crop impacts are discussed in the literature. Much more research, development, and dedicated field trials are needed to understand the impacts of these energy crops. Experience gained in Europe and elsewhere in recent years may be useful in helping address these issues.

SOIL QUALITY[2]

Soils are highly complex materials that require a careful interplay of physical, chemical, and biological processes to support high-productivity plant growth. Some of the more important qualities are described first, followed by a discussion of the ways in which energy crops may affect them.

By volume, soils typically consist of roughly half mineral matter, 3 to 5 percent organic materials, and roughly one-quarter each of water and air

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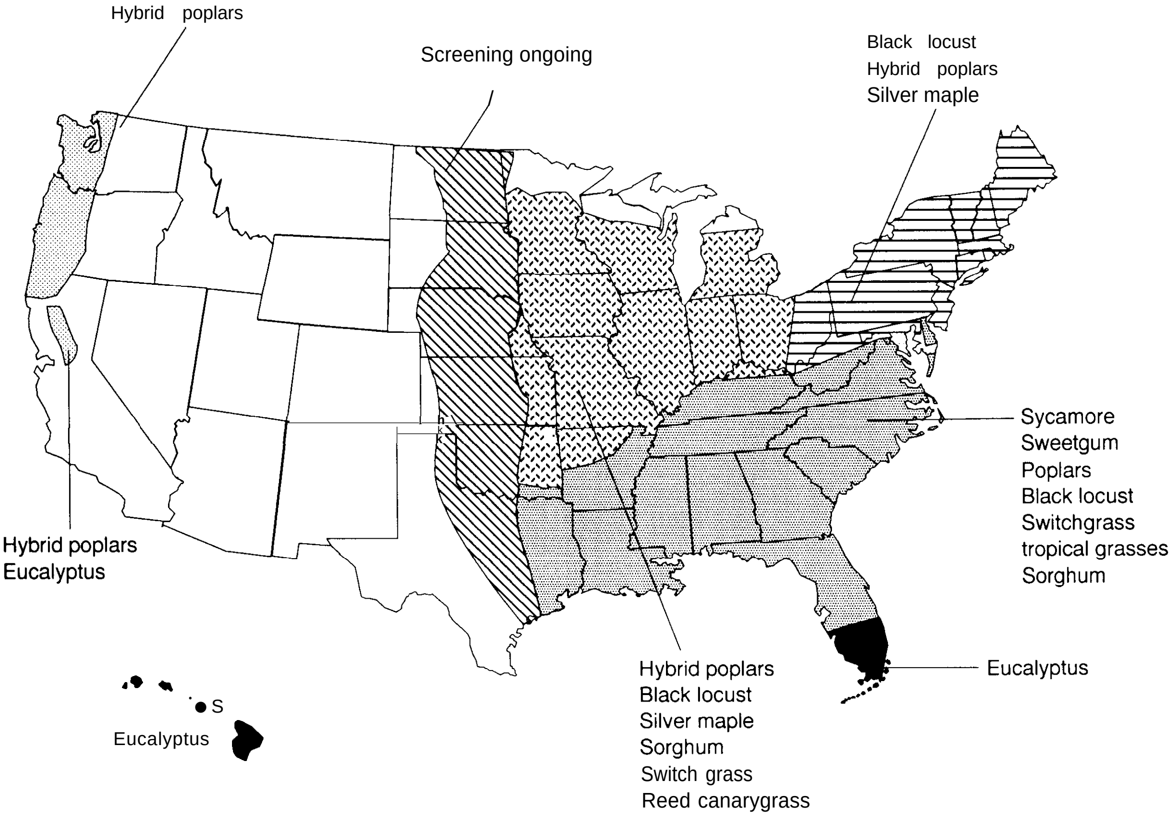
[1] Defining "natural habitat" may be difficult and controversial because past decades—sometimes centuries—of clear cutting, selective harvesting of economically valuable trees, and fire suppression have altered many U.S. forests, often leading to an increased concentration of plant species with lower economic or ecological value. Similar alterations have occurred over many other U.S. landscapes, including prairie and wetlands. **Although defining how much modification still qualifies as "natural"** is thus challenging, the term will be used broadly here to include all lands that support a significant quantity and variety of indigenous plants and animals. For [his report, only current or former agricultural lands, or highly degraded lands, are considered for energy crops.

[2] See W. Lee Daniels and Jody N. Booze-Daniels, "Potential Effects of Agricultural Biomass Cropping Systems on Soil Quality," contractor report prepared for the Office of Technology Assessment, Apr. 28, 1993; W. Lee Daniels and Jody N. Booze-Daniels, "Biomass Cropping Systems and Soil Erosion," contractor report prepared for the Office of Technology Assessment, Apr. 28, 1993; Philip E. Pope, "Impacts of Increased Use of Forest Resources on Soil Quality," Office of Technology Assessment contractor report, May 13, 1993; Nyle C. Brady, *The Nature and Properties of Soils* (New York, NY: Macmillan Publishing Company, 1984), 9th Ed. For a broader discussion of the future of soil management, see: F.J. Pierce and R. La], "Soil Management in the 21st Century," R. Lal and F.J. Pierce (eds.), *Soil Management for Sustainability* (Ankeny, IA: Soil and Water Conservation Society).

Figure 3-l—Potential EnergyCrops and Regions Applicable in the United States



This figure shows a limited set of potential energy crops and the regions within the United States where they might be grown. Many other species might be considered as well, including alder, ash~-kenaf, mesquite, etc.

SOURCE: Oak Ridge National Laboratory.

in the pore space. These proportions change dramatically with geographic region and type of soil, with soil depth (from more organic matter at the surface to more rock and less pore space further down), with how the soil is managed, and even with the local weather—recent rains or drought influence moisture and air (in pores) content.

Soils vary widely by the relative amounts of clay, silt, and sand in them. In effect, this is a classification of the relative amounts of different sized particles in the soil. Clays are mineral particles of less than 0.002 mm diameter, silt particles range from 0.002-0.05 mm in diameter, and sands range from 0.05–2.0 mm (by the definition of the USDA). These different sized particles provide substantially different “feels” to the soil, from the slick feel of wet clays to the coarse gritty feel of sand. Size distribution strongly affects such factors as soil porosity and density, soil structure, aggregation, strength, and other factors.

The particular minerals from which the soil is formed also play a key role. Soils of the southeastern United States have high iron and/or aluminum content, while Midwest soils contain a broad mix of minerals. The particular mix of minerals in a soil determines many of its properties.

Soil organic matter is typically a small percentage of the total soil mass but plays a critical role. Organic matter is primarily responsible for making soils loose and porous—i.e., keeping mineral particles from packing tightly together—and thus aids aeration and penetration by water as well as helping plant roots penetrate into the soil. Organic matter increases the water-holding ability of the soil; it is the major source of important mineral elements for plant growth such as phosphorus, sulfur, and nitrogen; and it also helps buffer soil acidity/alkalinity. Biological organisms play a key role in breaking down soil organic matter and freeing nutrients from dead plant matter for use by growing plants. Without constant replenishment of organic matter, soils can quickly become depleted and barren.

Addition of organic matter to the soil comes from either leaves, twigs, or other above-ground residues, or it can come from the dieback of roots with the seasons or with harvesting. The rate of turnover of organic matter is determined by many factors, including the type of organic matter, whether it is plowed into the soil, the temperature and moisture levels of the soil, the clay content of the soil, the degree of aeration of the soil, and others. Rates of organic turnover in the first year can be nearly 50 percent of the initial weight; the rate slows after the first year. Bioenergy crops such as switchgrass and short-rotation woody crops may substantially increase soil organic matter compared with conventional row crops, with overall gains in productivity and soil quality.

Soil nutrients are also provided directly from soil rocks and minerals and, of course, these are the original sources of most soil nutrients (other than nitrogen). The chemical and biological weathering processes that release these nutrients are, however, quite slow compared with the release of nutrients from soil organic matter. More importantly, clay and humus[3] particles have large surface areas and the ability to hold various nutrients (potassium, calcium, magnesium, etc.) on their surface, preventing leaching and making the nutrients available for plant growth. Nutrients such as nitrogen, sulfur, and phosphorus are primarily provided by microorganisms' conversion of organic matter in the soil into forms usable by plants. Soil acidity or alkalinity plays a key role in the relative availability of these different nutrients.

Many of the physical, chemical, and biological properties of soils can be strongly modified by different management techniques; of particular concern here is the potential impact of bioenergy cropping.

Physical

Key physical properties of soils that can be influenced by how the soil is managed include: soil density, porosity, permeability, and water-holding capacity; and soil temperature, thermal conductivity, and heat capacity.

The density of soils can range from as low as 0.13 g/cm^3 in the organic residue at the surface of the soil and from roughly 1 to more than 1.8 g/cm^3 in the deeper mineral soils. Densities above 1.4 g/cm^3 can impair the penetration of the soil by roots; above 1.8 g/cm^3 root penetration is virtually stopped. The use of heavy equipment for soil preparation or harvesting can compact the soil, especially on moist, fine textured soils. In some cases this can result in a “hard pan” just below the depth of plowing that limits deeper penetration by roots.

Compaction increases the overall bulk density and, more importantly, tends to squeeze down the size of pores in the soil. Smaller pores allow poorer aeration (depending on how sandy the soil is), reduced water permeability, and are more easily water logged than uncompacted soils with larger pores. Compaction can be minimized by harvesting when the soil is relatively dry and strong, by harvesting in the winter (if and when the ground is frozen), by minimizing the number of times that the soil is crisscrossed by equipment, by using relatively lightweight equipment with wide tires, and by avoiding rutting the soil or otherwise excessively disturbing it. These factors will tend to guide further development of equipment used to

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[3] Humus is the more stable part of soil organic matter. It typically consists of plant tissues that are resistant to soil microbes, slowly decomposing feces of various soil fauna, and microbial tissue.

plant, maintain, and harvest energy crops as well as how the crops are managed.

Energy crops generally have deeply penetrating roots. If they are restricted by a hard pan from penetrating below about 0.3 meter (1 foot), crop growth will be affected at some time after crop establishment when drought occurs or if nutrients are in somewhat limited supply. Energy crop growth can also be affected if a hard pan ponds water below the soil and generates anaerobic conditions which inhibit root growth and plant vigor.

Where hard pans already exist, there may be little alternative but to break them up. The extensive root systems of energy crops, fewer equipment passes, and increased carbon contributions to the soil should generally improve soil density and porosity, and may moderate the reforming of the hardpan.

Soil temperatures are influenced by:

- vegetative cover—vegetation reduces direct exposure of the soil to the sun, lowering temperatures (although heating can be beneficial in the northern climates in the spring when crops are first being established),[4] and also reduces loss of soil moisture;
- soil color-determines the amount of sunlight which is absorbed; and
- orientation with respect to the sun-determines how much of the incoming sunlight is intercepted by the soil.

Soil thermal conductivity and heat capacity are lower for organic soils than for mineral soils, and lower for dry than wet soils. Together, soil temperatures, thermal conductivity, and heat capacity help determine the microclimate for soil biota when establishing a new bioenergy crop or maintaining an existing crop. Management practices such as how much vegetative cover is maintained, how much surface residue is collected, or how much tillage is practiced then strongly influence these soil characteristics. For energy crops, soil temperatures appear to be lower except, perhaps, when they are first established (when temperatures are comparable) than for conventional agricultural crops. This helps maintain a higher level of soil organic matter with attendant soil quality advantages.

Chemical

Soil chemistry is determined by a delicate interplay of soil minerals, soil acidity/alkalinity, organic matter content, moisture content, and other factors. Soil minerals include a wide variety of clays and other silicate materials, and oxides of iron and aluminum. As the minerals weather, they gradually release elements (calcium, magnesium, potassium, etc.) in a form that plants can use as nutrients. Some of these minerals also attract and help to hold nutrients, reducing leaching rates.

Soil acidity/alkalinity strongly influence the availability of various plant nutrients. Acidic soils allow nutrients such as calcium, magnesium, and potassium to be more easily leached *or* converted into forms that plants cannot readily use. Similarly, alkaline soils may have little phosphorus, iron, manganese, or other nutrients. Soil acidity/alkalinity also influence the activity of soil microorganisms.

Soil acidity/alkalinity is influenced by many factors:

- the type of minerals in the soil and the extent to which they buffer acidity, etc.;
- the acidity of rain or other water inputs, the type of vegetation grown (soils under conifers are more acid than those under broadleaf trees), and the decomposition of organic matter;
- local rainfall (wet climates can have greater leaching of acid/alkaline materials);
- local atmospheric inputs such as SO_x from air pollution;
- and many others.

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[4] W.E. Larson, J.B. Swan, and F.J. Pierce, "Agronomic Implications of Using Crop Residues for Energy," William Lockeretz, (cd.), *Agriculture as a Producer and Consumer of Energy*, American Association for the Advancement of Science Selected Symposium No. 78 (Boulder, CO: Westview Press, 1982).

The use of chemical fertilizers and conditioners such as lime can allow soil acidity/alkalinity to be controlled and make up for an y particular nutrients which are limiting potential biomass productivity.

The nutrient most frequently deficient in soils is nitrogen.[5] The principal source of nitrogen in natural systems is the conversion of organic matter by microorganisms to forms that can be used by plants and by biological nitrogen fixation from the atmosphere. Losses of soil nitrogen can occur by leaching, volatilization by burning, erosion, and by conversion back into gaseous nitrogen (denitrification) through biological activity (by certain microorganisms when they cannot get sufficient oxygen due to poor aeration of the soil), or less frequently by chemical reactions.

Phosphorus is also a frequently limiting nutrient. As for nitrogen, phosphorus is often held primarily in organic forms, and particularly within the active microbes in the soil. The most intensive agricultural soils, however, may have more mineral phosphorus than organic phosphorus.

Energy crops affect soil chemistry because they generally raise soil carbon (organic matter content) compared with annual row crops. This can buffer soil acidity or alkalinity.[6] The organic matter also provides a surface to which fertilizers and pesticides will adhere rather than leach on through the soil. This has considerable benefit in managing these chemicals and reducing possible offsite migration. Energy crops also generally require substantially less fertilizer, herbicides, pesticides, or other agricultural chemicals than annual agricultural row crops (table 3-l).

Biological

Living organisms are essential to all productive soils; they digest dead plant matter, cycle nutrients essential for plant growth, and improve the soil structure. Such organisms include plants (flora) and animals (fauna); they range in size from microscopic bacteria to small mammals such as moles; and they have various roles. Some feed on plant residues, some on live plants, and some prey on other soil fauna. Energy crops appear to favor greater and more diverse microbial populations than typical agricultural rowcrops.[7]

Microflora such as bacteria and fungi begin the decomposition process of organic matter by attacking it chemically. Small animals such as beetles, millipedes, and sowbugs physically—by chewing into the organic matter (simultaneously increasing the opportunity for microflora to attack it)—and chemically (digestion) attack it. Earthworms eat their way through the soil, mixing plant residues and mineral soil, partially digesting it, and substantially improving the nutrient availability, soil aeration and drainage. Up to 30 or more metric tonnes of soil per hectare may pass through earthworms annually.[8] Microscopic insects and mites may pass 20 to 100 percent of the fresh organic matter through their bodies each year. Larger animals such as gophers, moles, prairie dogs, etc., burrow into the soil—mixing it and improving its structure through granulation.

Some fungi enhance plant growth. Mycorrhizae (“fungus root”) fungi form a symbiotic relationship with the roots of higher plants. The fungi receive sugars and other food materials from the root; and, in turn, the fungi improve root uptake of a number of important plant nutrients, including phosphorus, zinc, copper, calcium, iron, and others. The fungi also improve drought resistance of the plant. Bacteria, most notably those which fix nitrogen, play a key role in maintaining soil fertility as well.

Soil microbes also compete with each other for food and have developed substances that inhibit or kill other microbes. Important products from such microbiota include penicillin and streptomycin.

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[5] In hotter, more humid climates, phosphorus is often deficient.

[6] Thus, it can raise pH (make less acid) for some acid soils and can lower pH for some alkaline soils.

[7] Jack Ranney, Oak Ridge National Laboratory, personal communication, Sept. 1, 1993.

[8] Nyle C. Brady, *The Nature and Properties of Soils*, (New York, NY: Macmillan Publishing Company, 1984).

Table 3-I—Typical Erosion Levels and Agricultural Chemical Use of Selected Food and Energy Crops

Crop	Erosion (Mg/ha-yr)	Fertilizers Nitrogen (kg/ha-yr)	Phosphorus (kglha-yr)	Potassium (kg/ha-yr)	Herbicide (kg/ha-yr)
Corn	**21.8**	**135**	60	**80**	**3.06**
Soybeans	**40.9**	**10**	35	**70**	**1.83**
HECs	0.2	30	50	**90**	**0.25**
SRWCs	**2.0**	**60**	30	**80**	**0.39**

SOURCE: Lynn L. Wright and William G. Hohenstein (eds.), "Biomass Energy Production in the United States: Opportunities and Constraints," U.S. Department of Energy and U.S. Environmental Protection Agency, draft, August 1992.

Based on findings in Germany, the short rotation woody crop (SRWC) hybrid poplar changes agricultural land biota to biota more resembling forest soil environments (more worms, fewer beetles and spiders).[9] The knowledge of soil biology and microbial ecology is poor, however, so it is not known to what extent these results can be generalized—that SRWCs will restore soil biota to preagricultural conditions for different soils, crops, climates, and management practices. The increased soil carbon, lower soil temperatures, and more consistent soil moisture conditions, however, may at least partially restore native soil biota and their attendant benefits.

Before the widespread availability of commercial fertilizers, nutrients recycled by the biota were recognized as a major component of land productivity, and thus soil ecology ranked high among the agricultural sciences. In recent decades, however, this aspect of soil science has been largely neglected.[10] Use of artificial fertilizers can increase crop growth to such an extent that organic matter inputs and soil biota are increased substantially.[11] Energy crops generally will require a management approach using both fertilizers and organic matter improvement. This might be considered a hybrid system of low-intensity sustainable agriculture to attain high productivity.

Agricultural scientists generally are not alarmed about pesticides harming soil ecology in the near term: some research indicates that pesticides usually have minor and short-term impacts and side effects on soil microbiota other than those targeted. Such findings continue to be controversial, however.[12] Frequent applications of toxic chemicals can change the composition of soil biota communities, favoring species that can adapt to the new chemical environment.[13] Further, certain broad-spectrum pesticides may also kill earthworms or microscopic insects and mites that condition the soil; this can slow the rate of organic matter turnover and nutrient release for plant growth.

The impact of long-term use of such agricultural chemicals on land productivity is not known. Because methods are not sufficiently well developed to make practical differentiation among microbe species in the field, and soil invertebrates are seldom studied, the cumulative effect of chemical use on productivity cannot be fully measured. Crop rotations are also widely effective in disrupt-

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~ F. MakesChin, University of Munich, 1991; Jack Ranney, Oak Ridge National Laboratory, personal communication> Sept. 1, 1993.

[10] U.S. Congress, Office of Technology Assessment, *Impacts of Technology on U.S. Cropland and Rangeland Productivity,* OTA-F-166 (Washington, DC: U.S. Government Printing Office, August 1982).

[11] Richard P. Dick, "A Review: Long-Term Effects of Agricultural Systems on Soil Biochemical and Microbial Parameters," *Agriculture, Ecosystems and Environment,* vol. *40, 1992,* pp. 25-36.

[12] W. Lee Daniels, Virginia polytechnic and State University, personal communication, Sept. 1, 1993.

[13] See, for example: D.A. Crossley, Jr., Barbara R. Mueller, and Judy C. Perdue, "Biodiversity of Microarthropods in Agricultural Soils: Relations to Processes," *Agriculture, Ecosystems and Environment, vol. 40, 1992,* pp. 37–46.

ing disease cycles and maintaining soil microbial and enzyme levels and are often preferable to using agricultural chemicals.[14] Energy crop practices which now rely on multiyear monoculture need to recognize crop rotation benefits through innovative practices such as species mixes. Energy crop development has not yet pursued such innovative practices and may need to look toward range management and forestry for guidance.

The movement of agricultural chemicals beyond the field to which they are intended is also of concern. This can occur by groundwater contamination, runoff into streams, misapplication (such as drifting with the wind during aerial application), or by entering the food chain of animals or people.[15] During the crop establishment phase, energy crops raise these concerns just as does conventional agriculture. Compared with annual agricultural row crops, energy crops do not substantially lower the risk of agricultural chemical movement until their second or third year of growth.

Agricultural chemicals such as fertilizers, insecticides, herbicides, and fungicides have a variety of impacts on wildlife. Fertilizer runoff into surface waters can lead to eutrophication and can damage some aquatic species (see below). Herbicides generally have low toxicity for birds and mammals, but some have been shown to affect reproduction rates directly or indirectly. Insecticides, particularly the organophosphates (which are the most widely used insecticides in the United States), can kill some wildlife following application and can affect their reproduction. Overall impacts of these agricultural chemicals on wildlife are poorly understood. Some organophosphates may be used during energy crop establishment. After the crop becomes well established, herbicides are no longer needed. As the energy crops considered here are replanted only every 15 to 20 years, the use of herbicides is substantially reduced compared with usage needed for agricultural crops.

Insect, bird, and mammal predators that control pests but which have been damaged either through loss of habitat, agricultural chemicals, or other means make agricultural, forestry, or energy crops more susceptible to outbreaks of pests. Eastern tent caterpillars, southern pine beetles, and cottonwood leaf beetles, for example, are preyed upon heavily by various birds. This loss of predator species may require increased use of pesticides to maintain pest control.

Nutrient Cycling

Most nutrients available for plant growth in non-agricultural systems (in agricultural systems, nitrogen, phosphorus, and potassium are generally added annually) come not from atmospheric inputs or the gradual weathering of minerals (although these are the initial sources of these nutrients) but from decomposition of plant matter by microorganisms. Although standing and decaying biomass (above and below ground) might represent just a quarter of the total nitrogen in a forest system, for example, it accounts for most of that actually available for plant growth.

Harvesting energy crops can have several impacts on nutrient cycling. Nutrients are removed with the crop. Immediately following harvesting, warmer (more direct sunlight) and wetter (less water is taken up and transpired by vegetation) conditions in the soil may increase rates of decomposition and nutrient release just when vegetation is least available to make use of these nutrients. Leaching and other losses of nutrients then often follows, but are usually substantially less than the nutrient losses due to the removal of the biomass itself.

The quantity of nutrients removed by harvesting depends on the age of the biomass crop, the specific parts removed, and the time of year of the

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[14] Richard P. Dick, "A Review: Long-Term Effects of Agricultural Systems on Soil Biochemical and Microbial Parameters," *Agriculture, Ecosystems and Environment, vol. 40, 1992,* pp. 25–36.

[15] See, for example: National Research Council, *Pesticides in the Diets of Infants and Children* (Washington, DC: National Academy Press, 1993).

harvest. Young trees have proportionately more nutrients per unit biomass than older trees since leaves and branches have more nutrients than tree trunks and are a greater proportion of total biomass. In a four-year rotation of poplar, for example, nitrogen, phosphorus, potassium, and calcium content of leaves were typically 20 times greater than that of the trunks per unit biomass.[16] Timing the harvest for periods when nutrients are lower and removing primarily nutrient-poor material (tree trunks, bark, and major limbs) can reduce the tax on nutrients and help move toward more sustainable biomass energy systems. Nutrient losses can be reduced by leaving leaves and branches uniformly distributed across the entire site. Harvesting of herbaceous perennial energy crops faces similar considerations, but may nevertheless be somewhat more taxing of nutrients due to their higher nutrient content per tonne. Nutrient losses also increase if there is increased erosion, such as during planting.

Simply counting direct nutrient losses, however, may be insufficient in indicating the total impact (positive or negative) of energy cropping on the soil. Changes in the physical structure (i.e., compaction), chemistry, biological makeup (species composition and balance), and other aspects must also be considered.

Overall, annual row crops with complete removal of the biomass can reduce soil quality and productivity. Longer cycles and reduced biomass removal—such as with herbaceous perennials or short-rotation woody crops-can be neutral or can even improve soil quality in many areas compared with conventional agricultural monoculture. Limited tillage and turnover of organic matter to the soil will also enhance soil quality compared with systems that have frequent tillage and complete residue removal.

Site preparation for planting energy crops may involve extensive plowing/disking/subsoiling[17] of the land (although no-till practices have been evaluated). This can improve soil conditions for establishing the crop, but may also temporarily increase nutrient losses and erosion rates for up to several years—which may lead to reduced growth rates after three to four years and in the longer term. Disking also does not help deep compaction from heavy equipment; deeper disking may be impractical as it can damage the root systems of the crop.

Ultimately, rapid rotations and extensive biomass removal will require use of fertilizers or other means—including multiple or mixed cropping systems-of replacing lost nutrients. Mixed crops, for example, might include the use of nitrogen fixing species. This would reduce the need for applying fertilizers and could potentially improve habitat, as discussed below, but could also complicate some processes for converting these feedstocks into liquid fuels.

Soil Erosion[18]

There is little net natural soil erosion in areas with undisturbed, continuous vegetation. Typical rates are less than 0.5 tonne/hectare-year of soil lost, and this is also less than the typical rate at which new soil is formed through natural processes.

Erosion is increased above this natural rate when soils are directly exposed to runoff water either by tilling the soil or by removing the canopy

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[16] Philip E. pow, "Impacts of Increased Use of Forest Resources on Soil Quality," contractor report prepared for the Office of Technology Assessment, May 13, 1993, table 2.

[17] Subsoiling is done t. break up compacted soils (hard pan) below the surface.

[18] U.S. Congress, Office of Technology Assessment, *Impacts of Technology on U.S. Cropland and Rangeland Productivity,* OTA-F-166 (Washington, DC: U.S. Government Printing Office, August 1982); W. Lee Daniels and Jody N. Booze-Daniels, "Biomass Cropping Systems and Soil Erosion," contractor report prepared for the Office of Technology Assessment, Apr. 28, 1993.

of plants or plant residues protecting the soil.[19] When the protective canopy is removed, rainfall directly striking the soil can dislodge particles and, when the soil is saturated with water, carry them down the slope in the runoff.[20] The use of heavy equipment to plant, work, or harvest the crop can contribute to its erosion potential by compacting the soil and reducing the infiltration of water, thus increasing runoff. Large amounts of erosion can also occur along access roads to the cropped area.

In contrast, a protective cover of plants or residues breaks the impact of the rainfall and retains a portion; increases the infiltration of rainfall into the ground and thus delays the onset of runoff; helps hold the soil in place; and breaks up the flow of runoff, allowing suspended soils to drop out of the runoff before being swept out of the field. Contour plowing, contour strip cropping, terracing, minimum or no-till, and other techniques, for example, can also slow the loss of soil, and strips of vegetation can be used to filter sediments out of runoff before it leaves the field.

Annual erosion rates for lands with perennial energy crops will probably be in the range of 0.2 to 3.0 tonnes per hectare, based on projections and very limited field data. Without conservation measures during the crop establishment phase (the first year), however, erosion rates may parallel com at 10 to 20 tonnes/hectare. Such high rates drop rapidly in the second and subsequent years of growth when there is continuous cover, Harvesting is likely to increase erosion rates somewhat, but rates following harvesting will still be only a fraction of those during the crop establishment period. It is therefore important that soil conservation measures be employed during establishment.[21]

Soil erosion primarily occurs in a relatively few catastrophic events. For example, the soil is relatively unprotected following spring plowing and planting and before the crops have become well established. At this time, extreme downpours or high winds can result in large losses of soil, and particularly soil organic matter and nutrients concentrated in the upper layer of the soil. Energy crops such as HECs and SRWCs are only replanted every 15 to 20 years, and this greatly reduces the probability that the soil will be uncovered during an extreme downpour. This also emphasizes the importance of soil conservation measures during the energy crop establishment phase when soils are most vulnerable.

Soil erosion can also degrade soil structure.[22] Losses of organic matter and nutrients are especially costly to soil productivity, as discussed above. In addition, where the remaining soils have a high silt or clay content, they are even more susceptible to further erosion. In this case, the clay tends to form a crust which limits water infiltration. Energy crops should generally reverse the degradation of soil structure, but field monitoring is needed to verify this.

As topsoils are eroded, less productive subsoils must support plant growth. These subsoils are often low in nutrients, dense, and generally infertile. In much of the southeastern United States, for example, subsoils tend to be quite acidic, clayey, very low in available phosphorus and other nutrients, and relatively high in soluble aluminum which is toxic to plants. It is on such sites that some of the herbaceous perennial crops may be relatively productive and yet stabilize or partially restore some desired soil functions. Tree crops may fare less well due to often much lower productivity on such degraded sites.

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[19] Erosion rates do not represent net losses of soil because eroded soil does not simply vanish. Much of the soil moved by erosion remains in the same field, but is farther downslope or downwind, Soil is eventually lost, however, as it moves off fields into waterways or onto noncroplands. Soil quality is affected by soil movement because organic materials and other lighter components are moved first, leaving behind poorer soils.

[20] The focus here will be on water erosion, but similar considerations apply to wind erosion.

[21] Jack Ranney, Oak Ridge National Laboratory, personal communication, Sept. 1, 1993.

[22] W.E. Larson, F.J. Pierce, and R.H. Dowdy, "The Threat of Soil Erosion to Long-Term Crop production," Science, vol. 219, Feb. 4, *1983*, pp. *458-465*.

The actual amount of soil erosion varies widely depending on the intensity of the rainfall, the type and condition of soil, the slope length and pitch, the type and quantity of vegetation on it, and other factors.[23] In turn, the resultant productivity of a crop on eroded soil varies widely by the soil type, quality, and depth, by the region, by the type of crop, and other factors. The response of the crop to erosion is sometimes unpredictable. In general, loss of soil organic matter and fine clays reduces availability of plant nutrients, reduces soil nutrient-retention and water-retention capacity, and reduces plant rooting depth as the soil layer thins. Again, energy crops are believed to generally improve soil quality compared with conventional agricultural row crops, and early results from field monitoring in Virginia clay, Midwestern soil, and elsewhere support this.[24]

The average annual loss of soil from cultivated U.S. cropland was about 9.2 tonnes/hectare-year in 1987,[25] far higher than the estimated 1 tonne/ha-yr rate of natural soil formation and at the high end of the 2 to 11 tonnes/ha-year guidelines used by the USDA Soil Conservation Service for acceptable long-term losses. Currently, erosion losses in many areas exceed the established USDA-SCS guidelines even when following locally approved conservation practices. Although these losses can be serious, in many cases they are not easily observable. For example, loss of 10 tonnes/ha-year corresponds to a loss of 2.5 cm (1 inch) of topsoil over 30 years.

The impact of energy crops on soil erosion is potentially mixed, depending on what the energy crop is compared with, the type of energy crop grown and how it is managed (especially during establishment), how much residue is left on the soil following harvesting, the type of soil, the slope of the land, and plain luck. The key to low erosion rates is having continuous, dense cover on the soil. For example, on a particular type of soil with a 4 percent slope, soil erosion rates in the production of soybeans were 41 tonnes/ha, in the production of corn were 22 tonnes/ha, and in the production of a continuous perennial grass was just 0.2 tonnes/ha.[26]

HECs and SRWCs generally will have lower levels of erosion than conventional row crops and similar levels as well-maintained pasture. Detailed analyses for various energy crops, however, generally remain to be done and estimates of energy crop erosivity parameters remain to be verified. As energy crops push into marginal lands,[27] erosion rates could increase[28] and crop productivities could suffer.[29]

USDA benefits are only provided those farms with approved soil conservation compliance plans for their highly erodible lands. Perennial bioenergy crops generally could be used effectively on these lands. Currently, lands enrolled in the Conservation Reserve Program are taken out of production for 10 years and can only be harvested during that time if there is an extreme local drought. Rather than allowing these highly erosive lands to revert to conventional crops at the end of that 10 years, some have suggested that reduced (from CRP levels) incentives be considered to encourage converting these lands to energy crops.

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[23] The most common method of predicting potential erosion is with the Universal Soil Loss Equation which incorporates empirical factors for all these parameters. See: W.H. Wischmeier and D.D. Smith, *Predicting Rainfall Erosion Losses,* USDA Agricultural Handbook 537 (Washington, DC: U.S. Government Printing Office, 1978).

[24] Jack Ranney, Oak Ridge National Laboratory, personal communication, Sept. 1, 1993.

[25] U.S. Department of Agriculture, Soil Conservation Service, "Estimated Average Annual Sheet and Rill Erosion on Cropland, By State and Year," 1987 *National Resources Inventory,* Washington, DC.

[26] David Pimentel and John Krummel, "Biomass Energy and Soil Erosion: Assessment of Resource Costs," *Biomass,* vol. 14, 1987, pp. 15-38.

[27] That is, if the lands are marginal because of highly erodible soils or slopes, but not if they are marginal due to wetness or heavy soils.

[28] A.F. Turhollow, Jr., S.S. Shen, G.E. Oamek, and E.O. Heady, The *Potential Impacts of Large-Scale Biomass Production On U.S. Agriculture,* CARD Report 130, The Center for Agriculture and Rural Development, Ames, IA: Iowa State University, 1985.

[29] F.J. pierce, R.H. Dowdy, W.E. Larson, and W.A.P. Graham, "Soil productivity in the Corn Belt: An Assessment of Erosion's Long-Term Effects," *Journal of Soil and Water Conservation, vol. 39, No. 2,* March-April 1984, pp. 131-136.

The environmental impacts of the energy crops are likely to be mixed, however, compared with continuing the land under CRP.

Summary: Energy Crops and Soil Quality

The impact of energy crops on soil quality depends on the energy crop, the soil, the climate, the land use it is replacing, and many other factors. Extensive removal of biomass residues from energy cropland for use as fuel or feedstock can reduce soil organic matter levels and associated soil quality. Some high-productivity energy crops such as certain herbaceous perennials can, however, provide a net increase to soil organic content relative to row cropping due to their heavy rooting alone. Energy crops with limited till age and which return large quantities of organic matter (e.g., leaf litter) to the soil can improve soil quality compared with those that rely on frequent tillage or complete removal of crop residues. Such a protective layer of vegetative cover helps to provide shading, maintain soil moisture content, prevent erosion, and may offer other environmental services.

Use of heavy equipment for preparing the soil, or for planting, maintaining, or harvesting the energy crop must be done cautiously to avoid compacting the soil or otherwise damaging the soil structure. For energy crops, this is primarily of concern during establishment and harvesting on soils that are heavy and/or wet.

Soil chemistry—nutrient balance and acidity—can be more easily managed than soil physical properties, but may nevertheless require a rigorous program of soil testing and crop-specific additions of fertilizer, lime, and other inputs. Preliminary results from studies elsewhere (India, Virginia, Minnesota) suggest that acidity/alkalinity is buffered and soil structure is improved where HECs and SRWCs are in production compared with conventional agricultural practices. This is mainly due to increased organic matter content in the soil.[30]

A "minimum data set" of important soil properties-physical, chemical, and biological-could be developed for biomass production systems.[31] This data set could then be used to follow changes in lands used for bioenergy crops. It is much more important to follow changes over time than to measure a particular parameter, such as organic matter content, a single time. Similar data sets could be developed for surface and groundwater resources and for habitat (see below). This minimum data set could be developed in conjunction with extensive and carefully designed field trials.[32]

WATER QUALITY[33]

Energy crops may affect water quality either positively or negatively, depending on the way they are managed, the land use they displace, and the specific impact examined. With good management they may significantly reduce nonpoint pollution of surface waters from agricultural practices, with attendant benefits for water quality and fish habitat (box 3-A). With poor management, they could increase the runoff of sediment,

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[30] Jack Ranney, Oak Ridge National Laboratory, personal communication, Sept. 1, 1993.

[31] As one example, see W.E. Larson and F.J. Pierce, "Conservation and Enhancement of Soil Quality," *Evaluation for Sustainable Lund Management in the Developing World, vol. 2: Technical Papers,* Bangkok, Thailand, International Board for Soil Research and Management, 1991, IBSRAM Proceedings No. 12(2); M.A. Arshad and G.M. Coen, "Characterization of Soil Quality: Physical and Chemical Criteria," *American Journal of Alternative Agriculture,* vol. 7, 1992, pp. 25-30.

[32] Monitoring crop yields alone may not be an adequate indicator of soil quality because crop varieties are frequently changed in order to improve yields, irrespective of soil conditions.

[33] u.s. Congress, Office of Technology Assessment, *Impacts of Technology on U.S. Cropland and Rangeland productivity,* OTA-F-166 (Washington, DC: U.S. Government Printing Office, August, 1982); U.S. Congress, Office of Technology Assessment, *Beneath the Bottom Line: Agricultural Approaches to Reduce Agrichemical Contamination of Groundwater,* OTA-F-418 (Washington, DC: U.S. Government Printing Office, November 1990), W. Lee Daniels and Jody N. Booze-Daniels, "Biomass Cropping Systems and Water Quality," contractor report prepared for the Office of Technology Assessment, Apr. 28, 1993. See also: Jodee Kuske, "Water Quality and Forestry: January 1982–July 1990," *Quick Bibliography Series: QB 91-53, 221* citations from AGRICOLA, Water Quality Information Center, National Agricultural Library, Beltsville, MD, March 1991.

Box 3-A-impacts of NonPoint Water Pollution

Nonpoint water pollution, whether from agriculture or other activities, has a variety of impacts on U.S. water resources and fish and other wildlife.

Increased sedimentation of streams and other bodies of water, primarily from erosion, may destroy fish feeding and breeding areas. Streams may become broader and shallower so that water temperatures rise, affecting the composition of species the stream will support. **Riparian wildlife habitats change, generally reducing species diversity.**

Pollutants and nutrients associated with eroded sediments can have adverse impacts on aquatic environments. Concentrations of toxic substances may kill aquatic life, whereas nutrients in the runoff can accelerate growth of aquatic flora. This can aggravate the sedimentation problem and lead to accelerated eutrophication of water bodies. Eutrophication is a process that usually begins with the increased production of algae and plants. As they die and settle to the bottom, the micro-organisms that degrade them use **up the dissolved oxygen. Sedimentation also contributes to exhausting the oxygen supply, especially in streams and rivers, by reducing water turbulence. Thus, the aquatic ecosystem changes dramatically.**

Phosphorus and nitrogen are the major nutrients that regulate plant growth. Soil nitrogen is frequently leached or runs off into water supplies. Phosphorus, on the other hand, is “fixed” in the soil, so runoff typically contains relatively small amounts. Under normal conditions, therefore, phosphorus is more likely to be the limiting factor in aquatic plant growth. Since phosphorus (along with potassium, calcium, magnesium, sulfur, and the trace elements) is held by colloid material, however, it is abundant in waters receiving large amounts of eroded soil This can lead to eutrophication.

Natural eutrophication is generally a slow process, but man-induced eutrophication can be extremely rapid and can produce nuisance blooms of algae, kill aquatic life by depleting dissolved oxygen, and render water unfit for recreation. Replenishing the oxygen supply is a costly remedy because of the energy and equipment investment on the scale required.

SOURCE: U.S. Congress, Office of Technology Assessment, Impacts *of Technology on U.S. Cropland and Rangeland Productivity* OTA-F-166 (Washington, DC: U.S. Government Printing Office, August 1982); U.S. Congress, Office of Technology Assessment, *Beneath the Bottom Line: Agricultural Approaches to Reduce Agrichemical Contamination of Groundwater,* OTA-F-418 (Washington, DC: U.S. Government Printing Office, November 1990). W. Lee Daniels and Jody N. Booze-Daniels, “Biomass Cropping Systems and Water Quality,” contractor report prepared for the Office of Technology Assessment, Apr. 28,1993.

fertilizers, or pesticides into streams during the establishment phase. They may help control, or contribute to, nonpoint contamination of groundwater. They may influence water table changes, Nonpoint sources of water pollution may account for half or more of the remaining water problems in the United States;[34] energy crops may offer a tool not previously available to help deal with some of these water quality issues.

Nitrogen in some form is needed for any crop, including energy crops, to attain high productivity levels. Conventional agricultural practices have allowed nitrogen and other agricultural chemicals to enter water supplies in many areas. Nitrogen (in the form of nitrate) and, in some cases, pesticides and herbicides are the most frequent contaminants of groundwater. A 1990 EPA study found detectable levels of nitrates in half of the 94,000 community water systems tested, although almost all of these were well below the levels believed to cause problems.[35]primary contributors of nitrates to groundwater include improperly functioning

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[34] Council for Agricultural Science and Technology, “Water Quality: Agriculture’s Role,” *Task Force Report No.120, December* 1992.

[35] *A separate study* of 1,347 wells found only 1 to 2 percent exceeding health standards. See: J.W. Ranney and L.K. Mann, “Environmental Issues,” Lynn L. Wright and William G. Hohenstein, (eds.), *Biomass Energy Production in the United States: Opportunities and Constraints,* U.S. Department of Energy and U.S. Environmental Protection Agency, DRAFT, August 1992.

septic tanks, agricultural activities, and animal wastes at central facilities such as feedlots. Nitrates move readily through the soil and can quickly reach groundwater unless first taken up by plant roots and incorporated in plant growth or by microbes feeding on plant residues.

Energy crops can have significantly deeper and heavier rooting patterns than conventional agricultural crops, allowing greater uptake of nitrogen and other agricultural chemicals before they can migrate offsite. Root zones for many agricultural crops are less than 0.3 meters. Effective rooting depths vary from about 0.3 to 1 m for some herbaceous perennials and 0.6 to 2 m for some woody crops. The likelihood that chemicals can leach below these levels depends heavily on:

- the season—root uptake is low during the winter for many crops;
- the soil type and condition;
- the amount of rainfall;
- how heavily the chemicals are applied;
- the vigor and amount of energy crop—newly planted or harvested crops have little ability to absorb large quantities of chemicals, however useful they might be;
- the extent of soil microbial activity;
- and other factors.

Energy crops may also require less nitrogen fertilizer than agricultural crops. Extensive research on these and related issues is now underway at Oak Ridge National Laboratory for short-rotation woody crops, but there is little data for most herbaceous perennials. Results to date indicate a high degree of nitrogen uptake and cycling except when high levels of nitrogen are added during the first year of crop growth.

Sediment, phosphorus, pesticides, and herbicides are the primary contaminants of runoff. Phosphorus is strongly bound to the soil and is readily taken up by soil microbes. Consequently, there is little migration of phosphorus to groundwater, but erosion can carry large amounts of phosphorus with it. Runoff of phosphorus to surface waters can cause eutrophication of these waters with all the attendant problems. Energy crops can potentially reduce the problem of soil and chemical runoff by lowering the requirements for these inputs compared with conventional crops, by controlling and limiting erosion and runoff, and/or by serving as filter strips to limit runoff from agricultural lands.[36] The extent to which this potential is realized depends on the previous use of the land, how the energy crop is established and maintained, the soil type and slope, and other factors.

Nonfertilizer agricultural chemicals such as herbicides, fungicides, and insecticides can also move into groundwater or surface waters; energy crops are expected to use less of these chemicals than does conventional agriculture. The 1990 EPA survey of 94,000 community wells found 10 percent with detectable levels of one or more pesticides from past agricultural practice. Almost all of these cases were far below standard safety levels and thus posed little human health threat. They do, however, indicate the ability of such agricultural chemicals to migrate through the environment.

The extent to which a chemical is lost depends on many factors, including:

- possible misapplication of the chemical, such as spray drift to surface waters during aerial application;
- runoff during heavy rainfall closely following application of the chemical during planting, when erosion and runoff are most likely;
- the type of chemical and the strength of its binding to the soil and plants;
- how much is applied;
- how quickly it decomposes;
- the topography;
- the type of crop and how it is managed (no-till versus conventional row crops);
- and other factors.

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[36] To serve as a filter and to be harvested periodically for energy, energy crops may require more complex and careful management than typical for energy crops which do not serve such demanding multiple functions.

These are of concern for energy crops as well as for agricultural crops.

It is difficult to generalize about these agricultural chemicals and their fates. Conventional no-till agricultural crops, for example, will have higher soil moisture contents and humidity levels, perhaps leading to more rapid rates of some chemical decomposition, but may also require higher levels of chemical application. Nevertheless, due to lower levels of runoff, no-till crops tend to have much lower total losses of chemicals to surface waters. On the other hand, some chemicals that would decay in a relatively short time under normal aerobic conditions may nevertheless be fairly stable in the anaerobic soils of wetlands and may therefore accumulate.[37] Energy crops considered here will generally follow the model of no-till agricultural crops, but will use less agricultural chemicals.

Their fates are similarly uncertain when agricultural chemicals enter groundwater or surface water. In general, relatively little is known about how these chemicals degrade in groundwater. Some binding of these chemicals to mineral particles and some biodegradation do occur, depending on the mineral, acidity, temperature, type of bacteria present, etc. Groundwater and surface waters are also frequently interchanged, so that nitrogen or other chemicals in groundwater may move into surface waters and vice versa.

Finally, high-productivity energy crops may use 300 to 1000 tonnes of water per tonne of biomass grown.[38] In some areas, such demands could impact local groundwater supplies. How overdraft and recharge problems should be handled in the context of energy crops may pose substantial challenges. Energy crops may, however, offer a tool for water table management in poorly drained areas or a more robust crop for flood-prone zones.

AIR QUALITY[39]

Energy crops can impact air quality in a variety of ways, again depending on the particular energy crop, the land use it is replacing, and how it is managed. Compared with annual row crops, HECs and SRWCs are likely to reduce wind-blown dust and tillage dust (except during establishment); reduce the use of agricultural chemicals; and reduce the *use* of diesel powered equipment for preparing the soil and for planting and maintaining the crop, but in many cases may increase use for harvesting and transport. HECs and SRWCs are likely to increase all of these emissions compared with pasture and Conservation Reserve Program lands. Energy crops may also affect the emission of hydrocarbons from growing plants. Finally, energy crops take up carbon dioxide from the atmosphere and can sequester the carbon in the plant biomass and in the soil. The net cost/benefit of these changes in emissions in producing energy crops must be measured against the changes in emissions when they are used as a substitute for fossil fuels—for transport, electricity generation, or direct heat applications-considering the ambient air conditions in the locality affected by the emissions and total greenhouse gas emissions.

Wind-blown dust from land used to grow HECs and SRWCs should usually decrease compared with that from agricultural lands as the soil should

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[37] Atrazine may be an example. See: W. Lee Daniels and Jody N. Booze-Daniels, "Biomass Cropping Systems and Water Quality," contractor report prepared for the Office of Technology Assessment, Apr. 28, 1993.

[38] David O. Hall, Frank Rosillo-Calle, Robert H. Williams, and Jeremy Woods, "Biomass for Energy: Supply Prospects," Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams, (eds.), *Renewable Energy.' Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993).

[39] Steven Shaffer, "Air Quality Impacts from Agriculture Biomass production and Residue Utilization as Energy Feed Stocks," contractor report prepared for the Office of Technology Assessment, May 13, 1993.

have more continuous cover.[40] windblown dust could increase, however, in areas where agricultural crop residues are more intensively collected for energy rather than being left on the field to protect the soil from wind or water erosion. Dust generated during tillage-nominally 6 kgha of PM-10(particulates with a diameter of 10 microns or less) for each pass through a bare field[41]—should also be reduced, as most energy crops will be perennials, replanted every 15 to 20years.This is in contrast to the annual planting and maintenance of many conventional agricultural crops.

Field burning of agricultural residues will continue to be practiced in some areas, primarily on the West Coast, as a means of pest and weed control, to reduce residue volumes, and for other reasons. In some cases, however, the creation of a market for bioenergy may make it sufficiently attractive for farmers to collect residues and haul them to market rather than burn them on site. Burning these residues in a properly designed and operating boiler, furnace, gasifier, etc., produces much fewer emissions than field burning. In some areas such as California's Central Valley, clean air laws may limit field burning and thus encourage residue collection and use as fuel or feedstock.

Growing plants release a variety of hydrocarbons. Non-methane hydrocarbons are primarily isoprene, which accounts for 50 to 80 percent of the emissions from deciduous trees, and monoterpenes, which account for most emissions from conifers. Agricultural crops emit relatively little hydrocarbon. Estimated emission rates, with very large uncertainties, are roughly 5, 50, and 200 kg/ha-yr from agricultural crops, deciduous forests, and coniferous forests, respectively .[42]

Although such biogenic emissions[43] of hydrocarbons may be as much as twice those from anthropogenic sources during the summertime peak in the Lower 48 states, the biogenic emissions are spread over a much larger area than anthropogenic emissions and would result in relatively little ozone formation when NO_x concentrations are low, which is typical for many rural areas.[44] The impact of energy crops on hydrocarbon emissions will depend on the particular crop compared with the previous land use and the area cropped. Overall biogenic hydrocarbon emissions are unlikely to be dramatically changed. If there is a net increase[45] in the use of diesel-powered equipment for energy cropping, this could result in a slight increase in generation of ozone in rural areas, as this equipment could provide the NO_x that is now often lacking for ozone formation. Conversely, decreased use of diesel equipment compared with conventional row crops might re-

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[40] The wind erosivity of a particular soil depends on the type of soil, the field roughness, the local climate (rainfall and wind), the length of the field (how much time the wind has to loft particles), and the vegetative cover. Average wind erosion levels range from about 100 kg/ha-yr for wheat to nearly 500 kg/ha-yr for soybeans. Roughly 85 percent of U.S. cropland, pastureland, and rangeland has a potential wind erosivity too low to be of concern, 11 percent requires moderate conservation measures, and 4 percent requires careful soil management. See Steven Shaffer, "Air Quality Impacts from Agriculture Biomass Production and Residue Utilization as Energy Feed Stocks," contractor report prepared for the Office of Technology Assessment, May 13, 1993.

[41] U.S. Environmental protection Agency, Office of Air Quality Planning and Standards, "Control of Open Fugitive Dust Sources," EPA-450/3-88-008, 1988; U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, "Fugitive Dust Background Document and Technical Information Document for Best Available Control Measures," EPA-450/2-92-O04, 1992; cited in Steven Shaffer, "Air Quality Impacts from Agriculture Biomass Production and Residue Utilization as Energy Feed Stocks," contractor report prepared for the Office of Technology Assessment, May 13, 1993.

[42] Steven Shaffer, "Air Quality Impacts from Agriculture Biomass Production and Residue Utilization as Energy Feed Stocks," contractor report prepared for the Office of Technology Assessment, May 13, 1993.

[43] Estimates of biogenic emissions may be high or low by a factor of 3 or more due to uncertainty in the measurements of emissions, land use, and other factors.

[44] Charles Blanchard, Envair, personal communication, Aug. 24, 1993; U.S. Congress, Office of Technology Assessment, *Catching Our Breath; Next Steps for Reducing Urban Ozone,* OTA-O-412 (Washington, DC: U.S. Government Printing Office, July 1989); J.W. Ranney and L.K. Mann, "Environmental Issues," Lynn L. Wright and William G. Hohenstein (eds.), "Biomass Energy Production in the United States: Opportunities and Constraints," U.S. Department of Energy and U.S. Environmental Protection Agency, DRAFT, August 1992.

[45] This could occur if the land was previously idle or if the energy crop required more fuel for harvesting and transport than was saved by reducing planting and maintenance requirements.

duce rural ozone formation. These changes are unlikely to cause significant regulatory problems except in regions where ozone standards are already being approached or exceeded, such as California's Central Valley.

Use of agricultural chemicals and diesel fuel and their corresponding emissions will increase as idled or abandoned cropland is shifted over to energy crops. The intensity with which chemicals and fuels are used will, however, vary from conventional agricultural crops. Use of fertilizers, pesticides, herbicides, and fungicides may be less than conventional crops, depending on the particular energy crop grown and what it is being compared with; and use of diesel equipment will decrease for planting and maintenance operations compared with conventional crops but will increase for harvesting and transport due to the sheer volume of material handled. Standard emissions factors for diesel equipment are given elsewhere.[46]

Energy crops such as HECs and SRWCs typically contain 6 to 18 times[47] more energy than is required to produce them and haul them to the power plant or conversion facility. New power plant technology will maintain or reduce most emissions rates for biomass as compared with coal, most notably for sulfur. Emissions factors for renewable fueled (ethanol, methanol) transport are more complex, depending on a variety of fuel characteristics, the specific application, and other factors. The increased emissions due to energy cropping must also be compared with the potential emissions changes-potential decreases in SOs and NO_x and increases in particulate and certain organic compounds—in urban areas .48

HABITAT[49]

Wildlife have been broadly affected by agricultural activities. The most widespread problems are a result of expanding cropping and grazing into wildlife habitats, overgrazing riparian areas, and agricultural activities that contaminate aquatic habitats. Carefully designed and implemented, energy crops may moderate these impacts in some circumstances, depending on the particular energy crop, the previous land use, how the crop is managed, and which species are targeted. In other cases, energy crops may have mixed impacts. Energy crops can not, however, substitute for natural[50] habitat and are not intended to.

Early efforts to preserve species focused on captive breeding of particular species, usually those with considerable anthropomorphic appeal.

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[46] U.S. Environmental protection Agency, "Compilation of Air Pollution Emission Factors, vol. 2: Mobile Sources," AP-42, 1985.

[47] In contrast, the net energy balance for current corn to ethanol technologies ranges from break-even to 3 times more energy. See, for example: Lee R. Lynd, Janet H. Cushman, Roberta J. Nichols, Charles E. Wyman, "Fuel Ethanol from Cellulosic Biomass," Science, vol. 251, March 15, 1991, pp. 1318-1323.

[48] U.S. Congress, Office of Technology Assessment, *Catching Our Breath: Next Steps for Reducing Urban Ozone,* OTA-O-412 (Washington, DC: U.S. Government Printing Office, July 1989); Alan J. Krupnick and Paul R. Portney, "Controlling Urban Air Pollution: A Benefit-Cost Assessment," Science, vol. 252, Apr. 26, 1991, pp. 522-528; Jane V. Hall et al., "Valuing the Health Benefits of Clean Air," *Science,* vol. *255,* Feb. 14, 1992, pp. 812–817; J.G. Calvert, J.B. Heywood, R.F. Sawyer, and J.H. Seinfeld, "Achieving Acceptable Air Quality: Some Reflections on Controlling Vehicle Emissions," *Science, vol. 261,* July 2, 1993, pp. 37-45; Mine K. Yucel, "Methanol As An Alternative Fuel: Economic and Health Effects," *Economic Review: Federal Reserve Bank of Dallas,* September 1991, pp. *9–20.*

[49] Michael L. Wolfe, "Potential Impacts of Energy-Dedicated Biomass Production on Wildlife and Biological Diversity in the United States," contractor report prepared for the Office of Technology Assessment, Apr. 30, 1993; U.S. Congress, Office of Technology Assessment, *Technologies to Maintain Biological Diversity,* OTA-F-330 (Washington, DC: U.S. Government Printing Office, March 1987); U.S. Congress, Office of Technology Assessment, *Technologies to Benefit Agriculture and Wildlife—Workshop Proceedings* (Washington, DC: U.S. Government Printing Office, May 1985); James H. Cook, Jan Beyea, and Kathleen H. Keeler, "Potential Impacts of Biomass Production in the United States on Biological *Diversity,' 'Annual Review of Energy and the Environment,* vol. *16, 1991,* pp. 401-431. See also: M.G. Paoletti, D. Pimentel, B.R. Stinner, and D. Stinner, "Agroecosystem Biodiversity: Matching Production and Conservation Biology," *Agriculture, Ecosystems and Environment, vol. 40, 1992,* pp. 3-23; Robert M. May, "How Many Species Are There on Earth?" *Science,* vol. 241, Sept. 16, 1988, pp. 1441-1449. Elliott Norse, "Threats to Biological Diversity in the United States," U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, EPA Contract #68-W8-0038, September 1990; "Toward Ecological Guidelines for Large-Scale Biomass Energy Development," Report of a Workshop convened by the National Audubon Society and Princeton University, May 6, 1991.

[50] Op. cit., footnote 1.

Although these efforts were partially successful, scientists and policy makers have gradually recognized that the species which gain publicity are just the tip of the iceberg (box 3-B), but are useful icons in helping to save the less telegenic species as well. Further, they have found that the more effective means of saving all these species is not through last-minute desperation efforts but rather through conserving critical habitat for all the species in the region. Thus, attention has shifted from species to habitats to regional landscape ecology.

The impact of agricultural, forestry, and other land use practices on wildlife and habitat will first be examined below. Lessons will then be drawn from this experience, and applied to the potential design and management of energy crops.

Agriculture

As American settlers cleared forests and plowed prairie land for cultivation, species that were adapted to open areas prospered. The cottontail, bobwhite, crow, robin, red fox, skunk, and meadow mouse, for example, benefited as forests were opened to fields. Forest edge-loving species—"early successional" species—increased as more of their favored environment was available, but later declined as more forest was cleared, leaving little but fields. Other species—particularly forest interior, wetland, and larger species (such as wolves and bears) requiring larger home ranges-could not adapt to the changed environment and have reduced ranges and dimished population sizes or have been displaced. There is some disagreement as to the extent of the declines and the causes for some species. Two principal causes being examined for neotropical songbirds, for example, are tropical deforestation in Latin America and changes in breeding grounds in North America.

As crop yields on sloping uplands decline with erosion and fertility loss, farmers sometimes convert upland fields to pasture and drain lowlands for crops. Wetlands drainage removes habitat for migrating and resident waterfowl, and can remove the last remaining winter cover for some species of wildlife such as pheasants. The removal of fencerows and shelterbelts also reduces wildlife habitat and, in turn, the wildlife that live there.

Modem agriculture has generally increased the size of agricultural blocks and shifted from multiple crops to monoculture of just a few cash crops (table 3-2). Larger fields have less fencerow for habitat. Studies have found, for example, that five times as many birds use the perimeter of cornfields than use the center. Increasing field size is then found to decrease bird abundance per unit area logarithmically.

Field margins can also contribute to survival and health of predatory insects as well as pollinating insects.[51] For many predatory insects, however, the crop type and presence of agricultural residues plays a more important role.[52] These insects, of course, reduce damage from pests on crops.

Mechanization has led to the destruction of nests in, for example, hayfields. More generally, nesting activity is near zero in most conventional agricultural row crops. Nearly all nesting activity instead occurs in adjacent fencerows, shelterbelts, and idle land.

Agricultural waste grains may benefit some wildlife. For example, 80 percent of the U.S. population of sandhill cranes depend heavily on waste corn along the Platte River in Nebraska to provide the energy they need to continue their migration north.[53] More generally, these grains only supplement bird diets and, alone, may be

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[51] Jan Lagerlof, Josef Stark, and Birgitta Svensson, "Margins of Agricultural Fields As Habitats for Pollinating Insects," *Agriculture, Ecosystems, and Environment* vol. 40, 1992, pp. 117-124.

[52] C.J.H. Booji and J. Noorlander, "Farming Systems and Insect Predators," *Agriculture, Ecosystems and Environment* vol. 40, 1992, pp. 125-135.

[53] James H. Cook, Jan Beyea, and Kathleen H. Keeler, "Potential Impacts of Biomass Production in the United States on Biological Diversity," *Annual Review of Energy and the Environment, vol. 16,* 1991, pp. 401-431,

Box 3-B-What Is Biological Diversity?

Biological diversity refers to the variety and variability among living organisms and the ecological complexes in which they occur. Diversity can be defined as the number of different items and their relative frequency. For biological diversity, these items are organized at many levels, ranging from complete ecosystems to the chemical structures that are the molecular basis of heredity. Thus, the term encompasses different ecosystems, species, genes, and their relative abundance; it also encompasses behavior patterns and interactions.

Diversity varies within ecosystems, species, and genetic levels. For example:

- **Ecosystem diversity: A landscape interspersed** with croplands, grasslands, and woodlands has more diversity than a landscape with most of the woodlands converted to grasslands and croplands.
- Species diversity: A rangeland with 100 species of annual and perennial grasses and shrubs has more diversity than the same rangeland after heavy grazing has eliminated or greatly reduced the frequency of the perennial grass species.
- **Genetic diversity:** Economically useful crops are developed from **wild plants by selecting valuable inheritable characteristics. Thus, many** wild ancestor plants contain genes not found in today's crop **plants. An environment that includes both the domestic varieties** of a crop (such as corn) and the crop's wild ancestors has more diversity than an environment with wild ancestors eliminated to make way for domestic crops.

Concerns over the loss of biological diversity to date have been defined almost exclusively in terms of species extinction. Although extinction is perhaps the most dramatic aspect of the problem, it is by no means the whole problem. Other aspects include consideration of species having large habitat requirements of relatively pristine ecological condition, species whose movement is easily prevented with the slightest anthropogenic changes in the landscape, unique communities of species, and many others. These are just a few of the **aspects** of biological diversity that should be considered. Means of coping with these many aspects of biological diversity in the context of our lack of knowledge of biological diversity are being developed. "Fine filter" approaches deal with the potential loss of individual species; "coarse filters" focus on maintaining the integrity of entire ecosystems. Energy crops may offer an additional tool at the regional landscape level to assist such strategies.

SOURCE: U.S. Congress, Office of Technology Assessment, *Technologies to Maintain Biological Diversity,* **OTA-F-330 (Washington, DC: U.S. Government Printing Office, March 1987). For a more inclusive definition of biodiversity, see Allen Cooperrider, "Conservation of Biodiversity on Western Rangelands," Wendy E. Hudson, (cd.),** *Landscape Linkages and Biodiversity,* **(Washington, DC: Island** Press, 1991). For a discussion **of fine filters and coarse filters, see: Kathryrt A. Kohm, (cd.),** *Balancing on the Brink of Extinction: The Endangered Species Act and Lessons for the Future* **(Washington, DC: Island Press, 1991) (see especially the chapter by Malcolm Hunter); and Malcolm L. Hunter,** Jr., *Wildlife, Forests, and Forestry: Principles of Managing Forests for Biological Diversity* **(Englewood** Cliffs, NJ: Prentice Hall, 1990).

nutritionally inadequate, especially for the development of nestlings and young birds.[54]

The abandonment of farms can improve habitat for wildlife as it regenerates natural vegetation, but the diversity of species is still greatly reduced from the original flora and fauna for long periods.

Forestry

Conventional forestry management practices have also had an impact on habitat and wildlife. On industrially owned or managed lands, forestry management has generally focused on producing a more uniform product, faster, and at higher pro-

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[54] Michael L. Wolfe, "Potential impacts of Energy -Dedicated Biomass Production on Wildlife and Biological Diversity in the United States," contractor report prepared for the Office of Technology Assessment, Apr. 30, 1993.

Table 3-2—Major Cropland Usage, 1992

Crop	**Area planted** (million **hectares)**
Corn	30.8
Wheat	25.9
Hay	25.5
Soybeans	23.5
Other small grains	7.7
Cotton	5.7
Sorghum	4.9
Other field crops	5.3
Orchards	2.0
Vegetables	**1.6**
Total active	**132.9**
Idled	13.8
Short-term set-aside	7.7
Long-term set-aside (CRP)	14.2
Total cropland	170.4
Total pastureland	53.9
Total rangeland	164.4
Total agricultural land	388.7

SOURCE: Steven Shaffer, "Air Quality Impacts from Agriculture Biomass Production and Residue Utilization as Energy Feed Stocks," contractor report prepared for the Office of Technology Assessment, May 13, 1993.

ductivity. This has often resulted in very large stands of even-aged, rapid-growth single-species forests. In contrast, natural forests more often consist of numerous species and a wide range of habitats, ranging from climax forest to micro-openings in the canopy where a large tree has fallen and torn down the surrounding trees to large openings following a fire.

Forestry management practices have a variety of impacts on wildlife. Although early- and mid-successional species may benefit, species that depend on old-growth or forest interiors do not. Young, even-age stands of pine do not provide the large volumes of acorns that older stands of oak would provide as feed for a variety of animals; the downed wood and forest floor litter used by many species; nor the snags with nesting cavities used by many birds and mammals (see box 3-C). For example, some 20 species of birds in the southeastern United States use cavities for nesting, but only 12 have ever been documented using pine stands less than 50 years old. Patchwork harvesting also opens forest interiors, increasing the vulnerability of forest interior species to predators, including cats, possums, raccoons, skunks, squirrels, etc., which prey on the birds and/or their eggs and also encourages nest parasites such as the brown-headed cowbird.[55]

Further, conifers contain relatively high levels of compounds inimical to many insect herbivores; and conifer needles are relatively acidic, reducing the turnover of forest floor litter by invertebrates and making the soil itself acidic, thus allowing nutrients to leach out of the upper soil layers (see soil quality, above). Nonconifer energy crops will avoid this problem.

Together, these factors can reduce the richness of insect, bird, and other species under modern forest management. Use of nonindigenous tree species may similarly reduce species richness. There may be relatively few native species of insects that can live off a nonindigenous species and correspondingly few species of birds that can then be supported.

Riparian Zones and Wetlands

Riparian—adjacent to surface water—zones are particularly important habitat, but have been extensively lost due to clearing for agriculture and due to increased reliance on pumped irrigation water rather than ditch-irrigation with its riparian habitat. Compared with upland areas, riparian areas combine the basic resources of food, water, and cover; they have greater structural and plant diversity; they may have a wider range of microclimates for particular species; and they have

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[55] M.C. Brittingham and S.A. Temple, "Have Cowbirds Caused Forest Songbirds to Decline?" *Bioscience,* vol. 33, 1983, pp. 31–35; J.E. Gates and L.W. Gysel, "Avian Nest Dispersion and Fledging Success in Field Forest Ecotones," *Ecology,* vol. 59, 1978, pp. 871–883; D.S. Wilcove, "Nest Predation in Forest Tracts and the Decline of Migratory Songbirds," *Ecology,* vol. 66, 1985, pp. 1211–1214; Bill Lawren, "Singing the Blues for Songbirds," *National Wildlife,* August-September 1992, pp. 5-11.

Box 3-C-What Is the Value of a Dead Tree?

Traditional forestry practices have generally looked upon dead trees-either standing or fallen-as an economic loss, or a potential source of disease and insect infestation for the remaining stand, or a fire or safety hazard, or an impediment to replanting or travel. They have consequently managed forests to ensure use of as much of the biomass as possible and often burned the rest, leaving little behind. Research is now showing that dead trees play a key role in forest ecology and forest health.

Snags--standing dead trees-provide hundreds of bird, mammal, reptile, and insect species habitat for nesting, roosting, or foraging. At each stage in the decay of a snag, different species may make use of it. Birds such as the red-breasted nuthatch prefer to nest at the top of relatively young (less than 20 years) snags. Woodpeckers such as northern flickers prefer older snags both for the food they provide and for nesting. Other species of birds as well as some bats may roost under the loose bark sloughing off older snags. Cavities in the trunk may be used by a variety of birds as well as squirrels, bats, raccoons, and others. Where such snags have been removed, there have often been corresponding declines in the populations of birds and other animals dependent on them.

When a tree falls it continues to provide important habitat. Initially, a variety of wood-boring beetles tunnel into the tree; with them come various fungi and bacteria that speed the decomposition process. They are followed by various ants, termites, mites, centipedes, snails, salamanders, shrews, and others. The increasingly spongy tree serves as a nursery for new growth and holds large amounts of water to sustain this growth through drought. In some areas, downed trees maybe the primary sites for establishing new growth.

Mycorrhizae fungi form symbiotic relationships with the roots of many plant species and aid nutrient uptake by the roots. When their host dies, these fungi may die unless they encounter another host. Rodents such as the California red-back vole eat these fungi and help to disperse their spores for attachment to new growth. Removal of the rotting logs such rodents live in may hurt this virtuous cycle.

‘Trees that fall in streams similarly play a key role in aquatic habitats. The current of the stream tends to scour a pool around the log, providing aquatic species protection from being washed down the stream during high water and providing long-lasting pools during low water. Debris trapped behind the log decomposes and provides important nutrients for aquatic species rather than being washed away by the current.

Finally, in some areas dead trees may provide as much as half of the important organic matter inputs into the forest soil,

These ecological cycles may take centuries to become re-established in areas where traditional forest practices have cleared the land and burned the slash. The issue is not stopping use of timber, but rather how to use the insights from these ecological studies to improve forest health and productivity for both people and the many other species that use forest resources.

SOURCES: M.G. Raphael and M. White, “Use of Snags by Cavity Nesting Birds in the Sierra-Nevada California,” *Wildlife Monographs* vol. 86,1984, pp. 1-66; V.E. Scott, “Bird Response to Snag Removal in Ponderosa Pine,” *Journal of Forestry,* vol. 77, 1979, pp. 26-28, J.W. Thomas, R.G. Anderson, C. Maser, and E.L. Bull, “Snags,” in Thomas, (ed.), 1979; *Habitats in ManagedFores/s: The Blue Mountains of Oregon and Washington,* USDA Forest Service Agricultural Handbook No. 553, Washington, D.C.; Jerry Franklin, “Toward a New Forestry,” *American Forests,* vol. 95, No. 11–12, November–December 1989, pp. 37–45; James H. Cook and Jan Beyea, “Potential Impacts of Biomass Production in the United States on Biological Diversity,” *Annual Review of Energy and Environment, VOL 16, 1991,* pp. *401-431;* Jon R. Luoma, “An Untidy Wonder,” *Discover,* October 1992, pp. 86-95; Catherine Dold, “Study Casts Doubt on Belief in Self-Revival of Cleared Forests,” *New York Times,* Sept. 1,1992, p. C4; Jane E, Brody, “In Spring, Nature’s Cycle Brings a Dead Tree to Life,” *New York Times,* Mar. 24,1992, p. Cl; Jennifer Ackerman, “When the Bough Breaks,” *Nature Conservancy,* May/June 1993, pp. 8–9.

extended edges. These areas also play a critical role in protecting water quality—filtering runoff of sediment and agricultural chemicals, moderating stream temperatures, providing woody debris important for a variety of aquatic habitats, and providing food.

Wetlands are some of the earth's most productive ecosystems. They play a key role in supporting certain fish and shellfish during portions of their lifecycle, helping support more than 400 of some 800 species of protected migratory birds,[56] and in other areas, even providing some species of salamanders temporary (vernal) pools for breeding (year-round pools would support fish that would eat the salamander eggs and young).

Large water projects-dams, canals, irrigation—are the most obvious source of riparian habitat loss or degradation, but land use changes due to agriculture, timber harvesting, road building, development, and others are the most widespread and perhaps, overall, the most damaging. Impacts include increased silt and organic matter in water, changes in temperature, acidity, salinity, shading, flow rates, etc., and other factors. Maintaining even a small amount of stream bank forest can greatly reduce these impacts. Chemical and organic pollution is also due in large part to agricultural activities, now that industrial sources and city sewage are better controlled. In fresh water, fish, amphibians, mollusks, crayfish, insects and many other invertebrate phyla, and plants may be imperiled; a number are already extinct.[57]

The loss of structural diversity has similarly been detrimental for habitat in rangelands and elsewhere; details can be found elsewhere.[58]

Energy Crops and Habitat

The brief review above of the impact of agriculture, forestry, and other activities on wildlife habitat offers a variety of lessons for designing energy crops. Properly designed, energy crops can be used to manage or direct the regional landscape ecology—potentially serving as buffers around natural habitat, as corridors between fragments of natural habitat, or as habitat in themselves. How effectively the energy crop serves these roles depends on the particular crop, how it is managed (including use of chemicals, equipment, and harvesting cycle), and how the species it is designed to assist respond. There is very little field data to base conclusions on at this time; instead, the analysis here is based largely on theoretical models and of observations of wildlife interactions with other crops and altered habitats.

Energy crops are not, however, a substitute for natural habitat. Instead, they represent a compromise. In terms of habitat value, it would be preferable to let much of the idled crop land or other lands return to a natural state. Should global warming occur as currently projected, however, much of the habitat in the United States and elsewhere may be subject to sufficiently rapid climate change that the species/habitat that was intended to be protected may be unable to adjust or move quickly enough for the changed circumstances (figure 3-2). To avoid this, and more generally out of concern for potential global warming, it may be preferable to use idled crop land to produce greenhouse gas neutral[59] biomass energy. Energy crops are therefore of particular interest to the extent that they can be designed as a compromise between habitat concerns and greenhouse gas concerns.

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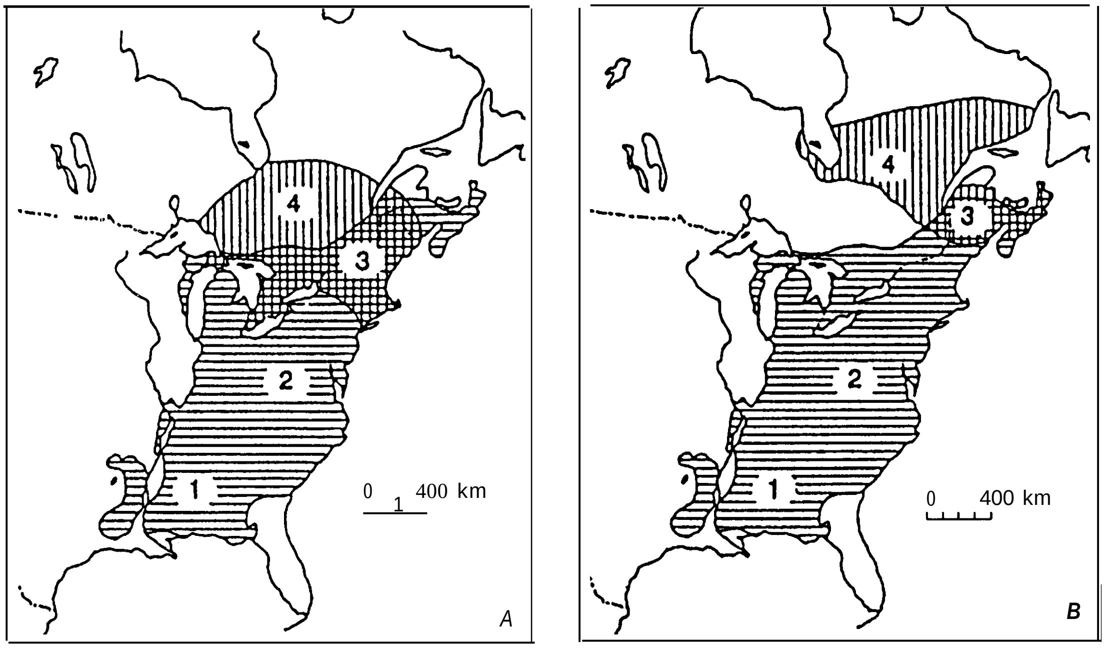
[56] Douglas A. Thompson and Thomas G. Yocom, "Uncertain Ground," *Technology Review,* August/September 1993, pp. *20-29.*

[57] J David Allan and Alexander S. Flecker, "Biodiversity Conservation in Running Waters," *Bioscience, vol. 43, No.* 1, January 1993, pp. 32–43.

[58] Michael L. Wolfe, "Potential Impacts of Energy-Dedicated Biomass Production on Wildlife and Biological Diversity in the United States," contractor report prepared for the Office of Technology Assessment, Apr. 30, 1993.

[59] If fossil-fuel-based agricultural chemicals, fertilizers, or transport fuels are used, bioenergy is not strictly greenhouse gas neutral. Typically, however, the net energy return (or greenhouse gas equivalence) is 6 to 18:1 for biomass energy to fossil energy inputs. This is for HECS and SRWCS. In contrast, current corn to ethanol production has much lower net energy gains.

Figure 3-2—Present geographic range of beech (horizontal lines) and potentially suitable range under doubled CO_2 (vertical lines) for two different climate models



These figures show the dramatic shift northward in the suitable range of a particular species. Although the two models disagree in the precise details, the overall extent of the shift predicted is similar.

SOURCE: Robert L. Peters and Thomas E. Lovejoy, (eds.), *Global Warming and Biological Diversify(New* Haven, CT: Yale University Press, 1992).

Understanding of biological diversity is growing rapidly, from simple concepts of species counts, to appreciation of the entire ecosystem and all the varied behavior patterns and interactions of its components. The ecology of a given region is determined by a number of factors, described broadly as the physical environment and species composition.

Three factors affecting biological diversity will be considered here: the relative structural complexity of the ecological system; the species diversity—including the species richness (the number of species present) and the species evenness (the relative number of different species); and the time scale.

In general, the more complex the vegetation (with many species, sizes, shapes, and ages of plants) in an area, the more complex the community of animals—insects,[60] spiders,[61] birds,[62] mammals,[63] etc.—it will support. Conversely, as vegetative structure is simplified, the community supported becomes progressively poorer. For example, the number of insect species in typical agricultural ecosystems such as corn can be half

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[60] D.R. *Strong,* J.H. Lawton, *R.* Southwood, *]n.reel.~ on Plants,* (Oxford: Blackwell Scientific Publications, 1984).

[61] C.L. Hatley and J.A. MacMahon, "Spider Community Organization: Seasonal Variation and the Role of Vegetation Architecture," *Environmental Entomology, vol. 9, 1980,* pp. 632-639.

[62] R.H. MacArthur and J.W. McArthur, "On Bird Species Diversity," *Ecology,* vol. 42, 1961, pp. 594–598; G.S. Mills, J.B. Dunning, Jr., and J.M. Bates, "The Relationship Between Breeding Bird Density and Vegetation Volume," *Wilson Bulletin, vol. 103,1991,* pp. 468-479.

[63] M. Rosenzweig and J. Winakur, "Population Ecology of Desert Rodent Communities: Habitats and Environmental Complexity," *Ecology,* vol. 50, 1966, pp. *558–572;* R.D. Dueser and W.C. Brown, "Ecological Correlates of Insular Rodent Diversity," *Ecology* vol. 61, 1980, pp. 50-61.

that found in pasture and one-third to one-tenth that found in deciduous forests.[64] It is the structural poverty of conventional agricultural monoculture that opens an opportunity for energy crops to improve habitat and biological diversity in a region.

Species richness and evenness are also important. In many cases, only the number of different species are listed without considering the number of individuals per species and whether it is sufficient to maintain a viable population, particularly in terms of genetics. Many believe that the goal of management should not be to maximize the number of species in a given area, but rather to ensure the conservation of threatened species and ecosystems.[65] After that is assured, the focus might turn to improving the conditions for less imperiled species and ecosystems.[66]

Finally, the time scale plays a key role. When a naturally forested area, for example, suffers a fire, a series of different plants—grasses, shrubs, small trees-colonize the area as it gradually regenerates back to full forest. Each of these plant ecosystems supports a different set of animals. This process is known as succession. Some animals, such as robins, field mice, rabbits, deer, etc., arrive early in the process. They thrive in the mixed forest-meadow habitat. Others prefer the low bushes and small trees of mid-succession. Still others require late succession or climax forest. Energy crops tend to favor the early- to mid-successional species, but may be designed to provide adequate habitat for mid- to late-successional species. This can be accomplished by leaving inclusions of old-growth vegetation within the energy crop area and by other means, such as artificial nesting structures, where necessary.

Energy crops can be designed to reduce many of the detrimental impacts on habitat and wildlife of conventional agriculture and forestry (see box 3-D). Energy crops may also serve as buffers around or corridors between fragments of existing natural habitat. So designing energy crops, however, involves numerous complex interacting factors that have been little studied in the context of energy cropping but which can be examined by analogy with fundamental principles of ecology and studies of agricultural, managed forest, and natural ecosystems. Four key issues will be examined here:

- the impact of habitat fragmentation;
- the potential of energy crops as buffers around fragments of habitat;
- corridors between fragments of habitat; and
- the impact of energy crop field operations.

Although plant genera native to the region are preferable, nonindigenous species with particularly favorable characteristics may be brought in under some circumstances. Especially versatile species—both herbaceous and woody-include hybrid poplar, black locust, eucalyptus, silver maple, switchgrass, sycamore, sweetgum, reed canary grass, salix (willow), sesbania, and leucaena.[67] Some nonindigenous species may, however, be able to escape cultivation and displace native vegetation or degrade wildlife habitats. Once established they become very difficult to eradicate.

Habitat Fragmentation

The natural landscape has become highly fragmented with several adverse impacts on species. As the area of habitat decreases, the number of different species it can support decreases. A single grizzly bear, for example, may need 75 km^2 of roadless land. On average, as the area of habitat is

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[64] David Pimentel et al., "Conserving Biological Diversity in Agricultural/Forestry Systems," *BioScience*, vol. 42, No. 5, May 1992, pp. 354-362; M.G. Paoletti, D, Pimentel, B.R. Stinner, D. Stinner, "Agroecosystem Biodiversity: Matching Production and Conservation Biology," *Agriculture, Ecosystems and Environment*, vol. 40, 1992, pp. 3–23.

[65] James W. McMinn, "Biological Diversity Research: An Analysis," U.S. Department of Agriculture Forest Service, Southeastern Forest Experiment Station, Asheville, NC, General Technical Report SE-71, September 1991.

[66] There continues to be debate about whether this or some other approach is the best strategy to follow.

[67] I Stjernquist, "Modem Wood Fuels," *Bioenergy and the Environment* (Boulder, CO: Westview Press, 1990), pp. 61-65.

Box 3-D-Prototype Ecology-driven Guidelines for Structuring Energy Crops

Plant species under consideration for use as bioenergy crops are primarily native species that evolved in the regions where they maybe used. These crops can provide greater structural diversity on a landscape level than typical agricultural **crops, and thus can enhance wildlife habitat. The extent to** which such habitat benefits are realized, however, depends on the careful application of ecological principles, as outlined in prototype guidelines below. These guidelines, however, should be considered only a starting point, requiring much further research. Further, these guidelines are based on principles drawn from studies of natural **ecosystems** and of highly simplified agricultural systems; there is little or no empirical data for energy crops themselves. Conducting dedicated field-trial research on the ecological interactions of natural systems with energy crops would be useful in order to guide the development of large-scale energy cropping.

Ecology-driven guidelines for structuring energy crops might include the following:

- Site. Energy crops should be concentrated on current, idled, or former agricultural, pasture, or other "simplified" or "marginal" lands. Energy **crops** should not be grown on naturally structured primary-growth forest land, wetlands, prairie, or other natural lands.[1]
- Species. Energy crops should combine two or more species in various ways in order to improve species diversity. This would preferably include the use of leguminous species or others with nitrogen-fixing capabilities to reduce the need for artificial fertilizers, and other combinations to reduce potential losses from disease or insects and thus reduce pesticide use. Non-invasive species which will not escape from cultivated plots are also preferred.
- **Structure.** Energy crops should combine multiple vegetative structures to enhance landscape diversity as needed by particular species. This could include various combinations of short-rotation woody crops, perennial grasses, and other dedicated energy crops, leaving small to large woody debris and other ground cover, as well as inclusions of natural habitat, as needed. These energy crops could also be used to provide structure to conventional agricultural monoculture through the addition of shelterbelts and fencerow plantings. Similarly, monoculture of energy crops should have shelterbelts or fencerows of other types of vegetation.
- **Lifetime. Landscape structure can also be made** more diverse by harvesting adjacent stands on different rotation cycles, including leaving some stands for much longer periods, if possible.
- **Non-indigenous species. Energy crops should use locally native species to the extent** possible. Native species or close relatives will harbor richer insect and other faunas.
- **Chemicals.** Crops should be chosen to minimize application of agricultural chemicals such as herbicides, insecticides, fungicides, and fertilizers, as discussed above.
- Unique features. Unique habitats and features such as small natural wetlands, riparian or other corridors, "old-growth" incisions, and shelterbelts should be preserved and enhanced by the energy crop.
- **Habitat assistance. Artificial nesting structures and** other additions to or supplements of habitat features should be provided where appropriate.
- **Research. Energy** crops should be studied carefully at all appropriate scales and on a long-term basis to better understand the best means of improving appropriate habitats **for desired species, both for the** energy crop itself as well as **for related agricultural, managed forest, and natural lands.** This should also be done on a regional basis, as appropriate.

SOURCE: Adapted from: Michael L. Wolfe, "Potential Impacts of Energy-Dedicated Biomass Production on Wildlife and Biological Diversity in the United States," contractor report prepared for the Office of Technology Assessment, Apr. 30, 1993; and from the discussion at the "Workshop on Environmental Impacts of Bioenergy Crops," Office of Technology Assessment, May 13, 1993.

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[1] Defining "natural habitat" maybe difficult and controversial because the past decades to centuries of, for example, clear cutting, selective harvesting of economically valuable trees, and fire suppression have altered many U.S. forests, often leading to an increased concentration of plant species with lower economic or ecological value. Similar alterations have ocurred over many other U.S. landscapes, including prairie and wetlands. Although defining how much modification still qualifies as "natural" is thus challenging, the term will be used broadly hereto include all lands that support a significant quantity and variety of indigenous plants and animals. For this report, only current or former agricultural lands or highly degraded lands are considered for energy crops.

decreased by a factor of 10, the number of species it can support is reduced by a factor of two. As the habitat area decreases, the number of individuals of a particular species decreases. Inbreeding increases, and the local population also becomes increasingly vulnerable to a single catastrophic event such as a fire or flood.

Fragments of habitat also have large edge effects. Changes in the type of vegetation, wind speeds, moisture, and other factors can modify the forest interior habitat for 20 to 200 meters or more into the forest.[68] The effective forest interior is then reduced proportionately, depending on the size of the forest fragment and the particular plant or animal species considered. For example, a 5-ha stand might effectively be all edge-like habitat, based on the vegetative structure and species supported. As the forest edge allows a variety of predators greater access to the wildlife inside, forest fragments may be affected even more than by the 20 to 200 m of edge effects alone.

Buffers

Energy crops may usefully provide habitat for some species. Perhaps as important, they might be useful to help isolate fragments of natural habitat from the disturbances described above. For example, if a wide strip of short-rotation wood-energy crop surrounded a 100-hectare fragment of natural habitat, it would reduce the edge effects described above. Forest interior species might then be able to use the habitat up to or even into the energy crop buffer. Instead of 10 ha of habitat, the effective area would be increased to 100 ha. In addition, predation may be reduced, although this is controversial and requires field verification.

For example, initial observations have found SRWC poplar plantations to provide substantial habitat value for birds, depending on the particular species, the age of the particular stand, and proximity to native habitat. From these studies, it appears that older SRWCs are more forest-like than field-like for many species. At younger ages or following harvest, however, it appears that SRWCs are more like old field and edge habitat.[69]

Corridors[70]

Energy crops might also serve as corridors between fragments of natural habitat, providing a protected habitat for wildlife traversing them. Corridors do not have to supply all of the necessities of life for a species using it, just those needed as the species moves along the corridor between patches of habitat; providing additional ecosystem services is desirable, but not essential. Corridors have become much discussed, but there is as yet little field data on how to design them for different species or on their overall effectiveness. Corridors that are effective for one species, such as bear, might actually harm another species such as salamanders-enticing them out of one fragment of habitat, but leading them to their death before reaching the next fragment. Corridors aiding the movement of desired species may also aid the movement of nonindigenous or undesirable species, potentially increasing the risk to those spe-

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[68] Blair Csuti, "Introduction: Conservation Corridors-Countering Habitat Fragmentation," Wendy E. Hudson (cd.), *Landscape Linkages and Biodiversity* (Washington, DC: Island Press, 1991); J. Ranney and M. Bruner, "Forest Edge Dynamics in Man-Dominated Landscapes" *Man-Dominated Landscapes* (Springer-Verlag, 1978).

[69] Wayne Hoffman, National Audubon Society, presentation at the Office of Technology Assessment workshop, May 13, 1993; see also Wayne A. Hoffman, James H. Cook, and Jan Beyea, "The Habitat Value of Short-Rotation Poplar Plantations: Avian Population Studies and Management Alternatives," Draft.

[70] As used here, "corridors" refers t. landscape features that help a particular species move between patches of habitat; it does not refer to utility rights-of-way, recreational greenways, or other such systems designed primarily to meet human requirements, although they may incidentally help wildlife. Literature on wildlife corridors is growing rapidly. See, for example: Wendy E. Hudson (cd.), *Landscape Linkages and Biodiversity* (Washington, DC: Island Press, 1991); Jon E. Rodiek and Eric G. Bolen, (eds.), *Wildlife and Habitats in Managed Landscapes* (Washington, DC: Island Press, 1991); Michael L. Wolfe, "Potential Impacts of Energy-Dedicated Biomass Production on Wildlife and Biological Diversity in the United States," contractor report prepared for the Office of Technology Assessment, Apr. 30, 1993.

cies that were targeted for help. Finally, a forest corridor that helps the movement of a forest species may be a barrier to a meadow species .7] Thus, a corridor may act as a filter, allowing the passage of some species and not others.

Corridors may serve three broad needs: to aid periodic migrations to reproduction sites; to allow foraging, roosting, or following seasonal food or other resources; or to allow occasional migration to ensure the continued viability of small isolated populations.[72]

Corridors must reflect the needs of their target species. Long corridors can be used only for fast-moving species. A 10-km-long corridor might easily support various species of birds, but not frogs—particularly if hungry racoons are prowling. A narrow corridor might be satisfactory for some species, but not for those which require the temperature, moisture, and other conditions of the forest interior. A narrow corridor may also increase predation. Many predators—ravens, jays, raccoons, house cats, etc.—prefer to forage where they can see and move most freely, near the edge of a forest. Species traversing a narrow corridor may then be running a gauntlet. On the other hand, wide corridors may not help some species as they will simply wander around in them, moving to the next patch of habitat only slowly at best.[73]

These are just a few of many factors that must be taken into account when designing energy crops to serve as buffers or corridors. Other factors must be considered as well, including the minimum viable area required to support a population of a species, species composition, ecosystem structure and function, and many others. These factors are as yet poorly understood and need detailed field trials to understand more fully these many complex interactions.

Field Operations

Finally, it is useful to consider the practice of energy cropping. For all energy crops, the timing of harvesting will have to be done to minimize interference with nesting or other key lifecycle activities of particular species. Bird reproduction rates, for example, are best on lands that remain undisturbed for at least three to five years or more. Harvesting should also leave sufficient cover for winter, for protection from predators, and for spring nesting activities.

Ground cover for wildlife is important in both herbaceous and woody crop systems. Woody debris, for example, increases the structural diversity of the site. Logs can serve as lookout sites; for nesting inside, alongside, or underneath; for courtship displays (certain grouse species); for food storage sites; or for food (insects for birds, mushrooms for red squirrels, etc.). Small mammals living inside decaying logs play a role in supporting coniferous forests by helping disperse the spores of mycorrhizal fungi which form an important symbiotic relationship with conifer roots and improve root function. Larger logs generally serve many of these functions better than small logs or woody debris. Box 3-C described some of these roles of dead trees in more detail.

Of course, all of these factors will have to be weighed against the economics of energy crop harvesting. The logistics and economics of harvesting small or irregular areas may limit use of such approaches to provide energy feedstocks.

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[71] Reed F. Noss, “Landscape Connectivity: Different Functions at Different Scales,” Wendy E. Hudson (cd.), *Landscape Linkages and Biodiversity* (Washington, DC: Island Press, 1991).

[72] Michael E. Soule, “Theory and Strategy,” Wendy E, Hudson (cd.), *Landscape Linkages and Biodiversity (Washington,* DC: Island Press, 1991).

[73] Michael E. Soule, “Theory and Strategy,” Wendy E. Hudson (cd,), *Landscape Linkages and Biodiversity* (Washington, DC: Island Press, 1991).

Table 3-3-Sources of Greenhouse Gases

Greenhouse Gas	Principal Sources
Carbon dioxide	Fossil-fuel combustion Deforestation, land use changes Cement production
Methane	Fossil-fuel production (coal mines, oil and gas wells, gas pipelines) Fossil-fuel combustion Landfills Rice cultivation Animal husbandry Biomass combustion and decay
Chlorofluorocarbons	Synthetics used in refrigerators and air conditioners Used in manufacturing processes as blowing agent, cleaning agent
Nitrous oxide	Fertilizers Fossil-fuel combustion Biomass combustion Deforestation and land use changes

Adapted from: Michael Grubb, *Energy Policies and the Greenhouse Effect, Volume tie: Policy Appraisal,* (Aldershot, Hants, England: Dartmouth Publishing Company, 1990); and Dilip R. Ahuja, “Estimating Regional Anthropogenic Emissions of Greenhouse Gases,” Forthcoming, T.N. Khoshoo and M. Sharma, (eds.), *The Indian Geosphere Biosphere, (New* Delhi, India: Vikas Publishing House, 1991).

GREENHOUSE GASES[74]

The environmental impacts described above are largely limited to the local rural region. Some activities—notably, the production and use of fossil fuels-can have a wider impact, including impacts on the global climate through the “enhanced” greenhouse effect.

The “natural” greenhouse effect is a well-established scientific fact. In the absence of the natural greenhouse effect, the average surface temperature of the earth would be –18 “C instead of the actual +15 °C. This +33 °C increase in average surface temperature is due to the presence of naturally occurring greenhouse gases—principally water vapor, carbon dioxide, and methane. Today, increases in atmospheric concentrations of these and other greenhouse gases due to the burning of fossil fuels, deforestation, and other human-induced changes in the biosphere are leading to an enhancement of this naturally occurring greenhouse effect. Table 3-3 lists some of the leading sources of these greenhouse gases and table 3-4 some of their key parameters. A recent review by over 200 leading scientists from 25 countries (the InterGovernmental Panel on Climate Change—IPCC) estimated that this increase in greenhouse gas concentrations will raise the average surface temperature of the earth (box 3-E).

Based on current models and under “Business-as-usual” scenarios, the IPCC scientists predict that global mean temperature will increase at a rate of about 0.3‘C per decade during the next century, a rate higher than that seen over the past 10,000 years.[75] This would mean a nearly 1 °C increase

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[74] U.S. Congress, Office of Technology Assessment, *Changing by Degrees: Steps to Reduce Greenhouse Gases,* OTA-O-482 (Washington, DC: U.S. Government Printing Office, February 1991); Intergovernmental Panel on Climate Change, *Scientific Assessment of Climate Change, Summary and Report,* World Meteorological Organization/U.N. Environment Program (Cambridge, United Kingdom: Cambridge University Press, 1990); Michael Grubb, *Energy Policies and the Greenhouse Effect, Volume One: Policy Appraisal* (Aldershot, Hants, England: Dartmouth Publishing Co., 1990); Intergovernmental Panel on Climate Change, “Policymakers Summary of the Potential Impacts of Climate Change: Report from Working Group H to the IPCC,” May 1990; J.T. Houghton, B.A. Callander, S.K. Varney (eds.) *Climate Change 1992: The Supplementary Report on the IPCC Scientific Assessment* (Cambridge, United Kingdom: Cambridge University Press, 1992).

[75] Very recently, evidence has emerged that past climate changes have also sometimes been quite rapid. See, for example: Richard A. Kerr, “Even Warm Climates Get The Shivers,” *Science,* voi. 261, Juiy 16, 1993, p. 292.

Table 3-4-Parameters for Key Greenhouse Gases

	CO_2	CH_4	CFC-11	CFC-12	N_2O
Atmospheric concentration					
Pre-industrial, 1750-1800	280 ppmv	0.8 ppmv	0 pptv	o pptv	288 ppbv
Present day, 1990	353 ppmv	1.72 ppmv	280 pptv	484 pptv	310 ppbv
Current annual rate of change	1.8 ppmv (0.5%)	0.015 ppmv (0.9%)	9.5 pptv (4%)	17 pptv (4%)	0.8 ppbv (0.25%)
Atmospheric lifetime (years)	(50-200)'	10	65	130	150
Global warming potential relative to carbon dioxide for today's atmospheric composition:					
Instantaneous potential, per molecule	1	21	12,000		
20-year time horizon, per kg	1	63	4,500	7,100	270
100-year time horizon, per kg	1	21	3,500	7,300	290
500-year time horizon, per kg	1	9	1,500	4,500	190
Contribution to radiant forcing,					
1765-1990	61%	23%	2.5%	5.7%	4.1%
1980-1990	55%	1570	5%	12%	6%
Reduction required to stabilize concentrations at current levels	60%	15-20%	70-75%	75-85%	70-80%

KEY: ppm(b,t)v = parts per million (billion, trillion) by volume

● Carbon dioxide absorption by the oceans, atmosphere, soils, and plants cannot be described by a single overall atmospheric lifetime.

SOURCE: Intergovernmental Panel on Climate Change, *Scientific Assessment of Climate Change, Summary and Report,* World Meteorological Organization/U.N. Environment Program (Cambridge, United Kingdom: Cambridge University Press, 1990).

over present-day global average temperatures by 2025 and a 3 'C increase by 2100. In addition to increases in mean global temperature, other effects expected to occur with increases in atmospheric concentrations of greenhouse gases include: increases in sea level,[76] and shifts in regional temperature, wind, rainfall, and storm patterns. These changes, in turn, are expected to:

- submerge low-lying coastal areas and wetlands, and increase the salinity of coastal aquifers and estuaries;
- impact human-built structures;
- shift a variety of vegetation zones (or destroy them if they can not move quickly enough)[77] and species ranges;
- alter plant metabolisms and productivities; and
- have a variety of other effects.

More recent studies have generally reaffirmed these findings[78] and raised even more serious concerns about the potential climate impacts beyond the year 2100.[79] The potential impact of and means of adapting to climatic change is the subject of a separate OTA study.[80]

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[76] The IPCC working group predicted an average rate of global mean sea level rise of about 6 cm per decade over the next century, 20 cm by 2030 and 65 cm by the end of the century with significant regional variations. This increase is primarily due to thermal expansion of the oceans and melting of some land ice.

[77] Different plant species migrate via different mechanisms, some through dispersal of airborn seeds, others via animal-borne seeds, etc. These different modes of seed dispersal result in different time lags for a species to move. Typical rates are 30 km per century; with projected global warming, dispersal rates needed are 10 times greater.

[78] Intergovernmental Panel on Climate Change, J.T. Houghton, B.A. Callander, S.K. Varney, (eds.), *Climate Change 1992:* The *Supplementary Report on the IPCC Scientific Assessment* (Cambridge, United Kingdom: Cambridge University Press, 1992).

[79] Syukuro Manabe and Renal J. Stouffer, "Century-Scale Effects of Increased Atmospheric CO_2 on the Ocean-Atmosphere System," *Nature,* vol. 364, 1993, pp. 215-218.

[80] U.S. Congress, Office of Technology Assessment, *Preparing for an Uncertain Climate,* forthcoming.

Box 3-E-Highlights of the Intergovernmental Panel on Climate Change 1990 Scientific Assessment

Several hundred scientists from 25 countries prepared and reviewed the scientific data on climate change **under the auspices of the World Meteorological Organization and the United Nations Environment Program. This Intergovernmental Panel on Climate Change summarized their** findings as follows:

The **IPCC** is **certain** that:

- there is a natural greenhouse effect which already keeps the Earth warmer than it would otherwise be.
- emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface. The main greenhouse gas, water vapour, will increase in response to global warming and further enhance it.

The IPCC calculates with confidence that:

- atmospheric concentrations of the long-lived gases (CO_2, N_2O, and the CFCs) adjust only slowly to changes in emissions. Continued emissions of these gases at present rates would commit us to increased concentrations for centuries ahead. The longer emissions continue to increase at present-day rates, the greater reductions would have to be for concentrations to stabilize at a given level.
- the long-lived gases would require immediate reductions in emissions from human activities of over 60 percent to stabilize their concentrations at today's levels; methane would require a 15 to 20 percent reduction.

Based on current model results, the IPCC predicts that:

- under the IPCC Business-As-Usual Scenario, global mean temperature will increase about 0.3 °C **per decade (with an uncertainty range of 0.2** to 0.5‘C per decade); this is greater than that seen over the past **10,000 years. This will result in** a likely increase in global mean temperature reaching about 1 °C above the present value by 2025 and 3 ‘C before the end of the 21st century,
- land surfaces will warm more rapidly than the ocean, and high northern latitudes will warm more than the global mean in winter.
- regional climate changes will differ from the global mean, although our confidence in the prediction of the detail of regional changes is low. Temperature increases in Southern Europe and Central North America are predicted to be higher than the global mean, accompanied on average by reduced summer precipitation and soil moisture.
- global mean sea level will rise about 6 cm per decade over the next century, rising about 20 cm by 2030 and 65 cm by the end of the 21st century.

All **predictions are subject to many uncertainties with regard to the timing, magnitude, and regional patterns of climate change** due **to incomplete understanding of:**

- sources and sinks of greenhouse gases,
- clouds,
- oceans, and
- polar ice sheets.

These processes are already partially understood, and the IPCC is confident that the uncertainties can be reduced by further research. However, the complexity of the system means that surprises cannot be ruled out.

The IPCC judgment is that:

- Global mean surface air temperature has increased by 0.3 to 0.6 ‘C over the last 100 years, with the five global-average warmest years occurring in the 1980s. Over the same period global sea level has increased **by 10-20 cm.**
- The size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus, the observed temperature increase could be largely due to natural variability; alternatively, this variability and other human factors could have offset a still larger human-induced greenhouse warming, The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more.

SOURCE: World **Meteorological Organization, U.N. Environment Program, intergovernmental Panel on Climate Change,** *Scientific Assessment of Climate Change, Summary and Report* (Cambridge, United Kingdom: Cambridge University Press, 1990).

In 1985, according to estimates for the IPCC Working Group III, three-fourths of annual global energy sector CO^2 emissions came from the industrialized market countries and the centrally planned European countries (including the former U.S.S.R.); about 20 percent came from the United States.

Controlling these emissions would slow potential global warming. Emission control strategies that countries could consider today include improved energy efficiency and cleaner or nonfossil energy sources. These strategies may also have economic benefits. Biomass energy could play an important role in such strategies.

Biomass as a Carbon Sink or Offset

Biomass can be used as a carbon sink or, more significantly, as a fossil fuel offset in order to slow the increase in atmospheric concentrations of carbon dioxide due to fossil fuel combustion. The potential contribution of biomass energy crops to other greenhouse gases, such as methane and nitrous oxide, and the potential impact of biomass energy crops on soil carbon balances should also be considered.[81] Only the direct carbon impacts will be considered here.

As a carbon sink, biomass is grown to absorb carbon dioxide from the atmosphere—which is then incorporated into the plant itself—and the biomass is then possibly put into some form of long-term storage. Storage options range from simply increasing the standing volume of trees,[82] to greater use of wood as a building material,[83] to harvesting the biomass so that more can be grown and storing it in dedicated sites.

These carbon "sequestration" strategies suffer several shortcomings. There is often little economic return from the sequestered biomass and generally an economic cost;[84] and if the biomass is left standing, the amount of biomass that can be sequestered is limited by the maturing of the tree.

As a fossil fuel offset, biomass can be used as a fuel in place of coal, oil, or natural gas.[85] If grown on a renewable basis, biomass makes almost no net contribution to rising levels of atmospheric carbon dioxide.[86] In addition, biomass energy crops may provide a net increase in soil carbon as well as in standing biomass, depending on the previous use of the land.[87] Biomass can be burned directly to power steam boilers or gasified to power gas turbines coupled to electric generators. Biomass can also be converted to ethanol or methanol and used to fuel transport. In the longer term, hydrogen derived from biomass may be a valued alternative fuel.

Growing, harvesting, transporting, and processing biomass as a fossil fuel offset make this an initially more costly strategy than carbon sequestration—i.e., simply growing trees. Sale of the biomass energy partially compensates for these

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[81] Energy crops will also tend to increase soil carbon inventories to as much as 30 to 40 Mg/ha over 20 to 50 years, when replacing cropland. This is roughly twice as much carbon as cropland carries and half that found in forestland. See: J.W. Ranney and L.K. Mann "Environmental Issues," in Lynn L. Wright and William G. Hohenstein, (eds.), "Biomass Energy Production in the United States: Opportunities and Constraints," U.S. Department of Energy and U.S. Environmental Protection Agency, DRAFT, August 1992.

[82] "Carbon Storage and Accumulation in United States Forest Ecosystems," U.S. Department of Agriculture, Forest Service, General Technical Report WO-59, August 1992.

[83] Jim L. Bowyer, "Tree Planting, Wood Use, and Carbon Sequestration," Testimony before the Subcommittee on Energy and Power, Committee on Energy and Commerce, U.S. House of Representatives, Washington, DC, July 29, 1993.

[84] Kenneth R. Richards, Robert J. Moulton, and Richard A. Birdsey, "Costs of Creating Carbon Sinks in the U.S.," IEA Carbon Dioxide Disposal Symposium, Oxford, England, Mar, 29–31, 1993; D.H. Rosenthal, J.A. Edmonds, K.R. Richards, and M.A. Wise, "Stabilizing U.S. Net Carbon Emissions by Planting Trees," U.S. Department of Energy and Battelle Pacific Northwest Laboratories, Washington, DC, 1993.

[85] D.O. Hall, H.E. Mynick, and R.H. Williams, "Alternative Roles for Biomass in Coping With Greenhouse Warming," *Science and Global Security*, vol. 2, 1991, pp. 1 13–151.

[86] Currently, some fossil fuel—typically 5 t. 15 percent of the energy value of the biomass crop---is used in the form of agricultural chemicals or diesel fuel.

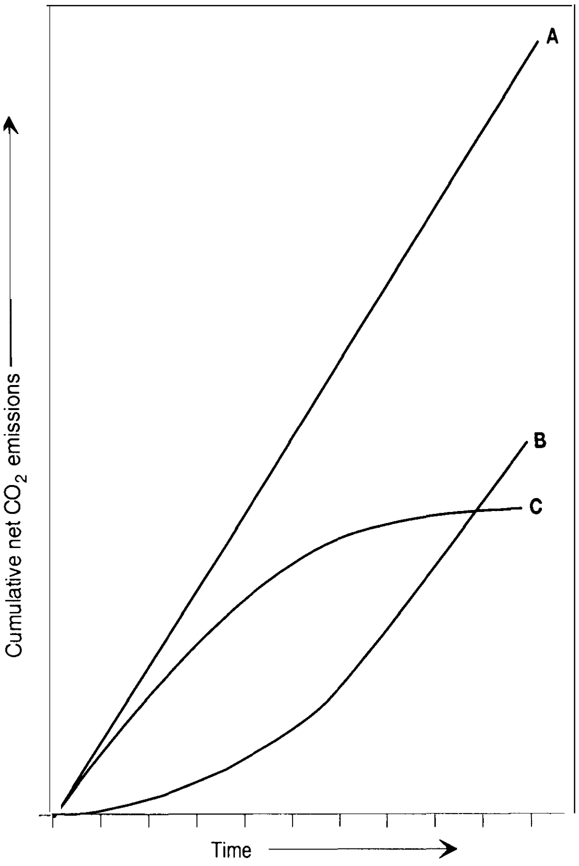
[87] L L. Wright and E.E. Hughes, "U.S. Carbon Offset Potential Using Biomass Energy Systems," *Journal of Water, Air and Soil Pollution*, in press. See also footnote 81.

costs, however, and with further development biomass energy may become a lower cost option than fossil fuels. Biomass is also likely to be one of the lowest cost of the renewable fuels for many applications.[88] Land can be used to grow biomass fuels on a continuous basis. This is in contrast to sequestration strategies for which the annual carbon storage per unit land area declines as the forest matures. Figure 3-3 illustrates the relative merits of carbon sink (sequestration) versus fossil fuel offset strategies. Offset strategies have greater long-term potential to control atmospheric carbon dioxide[89] because they can be continued indefinitely whereas, carbon sink strategies are limited by maturation of the tree. Offset strategies also have the potential to control carbon dioxide emissions cost effectively as they can substitute for the fossil fuel; sink strategies will be a net economic cost.[90]

CROPPING PRACTICES

Numerous cropping systems have been developed for conventional crops, including double and even triple cropping (including intercropping and succession cropping); a variety of crop rotations; and various forms of intercropping and agroforestry. Hundreds of these systems are in use. These systems have been developed to reduce disease and insect infestations, control weeds, improve water utilization, improve soil quality and control erosion, and improve productivity. Multiple cropping and other systems can also improve the utilization of farm capital equipment and labor and reduce the risks of failure of any one particular crop. The practicability of these various cropping systems depends on the soil, type of crop, local climate and rainfall, and other factors. Similar development of bioenergy cropping systems has not yet been done, but may have considerable promise. Extensive

Figure 3-3—Schematic representation of cumulative net emissions of CO_2 as a function of time for various combinations of a coal-fired electric power plant and energy crop management strategies



Path A shows the steady increase in cumulative CO_2 emissions into the atmosphere from the coal-fired power plant. Path B shows the cumulative emissions of CO_2 from the power plant less that taken up by growing young trees sufficient to initially balance the power plant emissions. As the trees mature they take up less and less CO_2 and eventually the emissions parallel path A. Path C represents emissions from a power plant which gradually shifts over to complete use of sustainably grown biomass feedstocks. Planting a large area (strategy B) and then using the biomass as a substitute for coal could fully offset emissions.

SOURCE: Adapted from: Greg Marland, "Strategies for Using Trees to Minimize Net Emissions of CO_2 to the Atmosphere," Testimony before the Subcommittee on Energy and Power, Committee on Energy and Commerce, U.S. House of Representatives, Washington, DC, July 29, 1993.

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[88] Robert H. Williams, "Fuel Cells, Their Fuels, and the U.S. Automobile," First Annual World Car 2001 Conference, University of California at Riverside, Riverside, CA, June 20-24, 1993.

[89] Greg Marland, "Strategies for Using Trees to Minimize Net Emissions of CO_2 to the Atmosphere," testimony before the Subcommittee on Energy and Power, Committee on Energy and Commerce, U.S. House of Representatives, Washington, DC, July 29, 1993.

[90] D.O. Hall, H.E. Mynick, and R.H. Williams, "Alternative Roles for Biomass in Coping With Greenhouse Warming," *Science& Global* Security, vol. 2, 1991, pp. 113-151.

research and dedicated field trials are needed to evaluate the relative costs and benefits of various energy cropping systems. An extensive review of conventional cropping systems, their impacts, and their extension to bioenergy crops is given elsewhere.[91] In turn, these multiple cropping systems have a variety of impacts on local biological diversity.[92]

CLOSE

Compared with conventional agricultural row crops, energy crops may have positive environmental impacts, depending on the specific energy crop, the previous use of the land, management practices, and other factors. Under these circumstances, energy crops may improve soil quality and reduce soil erosion, improve water quality—particularly by reducing runoff and serving as riparian filters, and may provide habitat benefits themselves and as buffers around or corridors between fragments of natural habitat. Compared with hay, pasture, well-managed Conservation Reserve Program, and other lands, however, HECs and SRWCs will have mixed environmental impacts. Finally, energy crops may provide an effective offset to fossil fuel emissions of greenhouse gases.

Due to the little energy crop-specific data currently available and the corresponding heavy reliance on conventional agriculture analogs, dedicated long-term studies of energy crops are needed. These would focus on soil quality—including physical, chemical, biological, and other parameters-and overall site productivity, water quality, air quality, habitat, greenhouse gas emissions, and other issues and should be examined on a full fuel cycle basis compared with alternative fuels and technologies or other policies. With these and other data, lands proposed for extensive bioenergy cropping could be mapped by their topography, soil type, current usage, habitat value, and other factors and classified by their potential environmental impacts. Such Geographic Information Systems could be a valuable tool in realizing the potential of these energy crops at the local and regional level.

Much research, development, and demonstration is needed to assure environmentally sensitive ***and*** cost-effective energy crops; there are no short-term answers. The development of a bioenergy agenda to meet these goals poses substantial challenges. This is the focus of the following chapter.

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[91] Raymond N. Gallaher, "Bioenergy Cropping Systems, Sources, Management, and Environmental Considerations," Contractor Report for the Office of Technology Assessment, May 13, 1993.

[92] David Pimentel, et al., "Conserving Biological Diversity in Agricultural/Forestry Systems," *Bioscience, vol. 42, No. 5,* May 1992, pp. 354-362.

The Bioenergy Agenda 4

For bioenergy to make a substantial contribution to the U.S. energy mix, a number of technical, economic environmental, commercialization, and policy issues must be addressed. Two of these will be examined briefly here: research, development, and demonstration of environmentally sound energy crops; and market distortions and barriers which threaten to substantial y slow commercial adoption of these technologies.

RESEARCH, DEVELOPMENT, AND DEMONSTRATION

Research, development, and demonstration (RD&D) is needed at all levels of biomass energy systems. This includes RD&D on: high-productivity crop varieties; their planting, maintenance, and harvesting; their environmental impacts; their transport and storage; and their conversion to fuels or electricity. The focus here will be on their environmental impacts and how these relate to other aspects of biomass energy systems.

Chapter 3 discussed the environmental impacts in some detail. Many of the impacts noted there were based on studies of conventional agricultural crops and were extended by analogy to energy crops; there have been few large-scale or long-term field studies of energy crops themselves. These impacts need to be carefully researched in dedicated field trials of energy crops:

Soil quality. Key areas of RD&D include: the development of a "minimum data set" of key soil physical, chemical, biological, and other parameters as a means of monitoring soil quality over long periods of time for different crops and management regimens; nutrient cycling, particularly of biochemical processes; the return of organic matter to the soil under various intensive energy crops and cropping systems; and the impacts of neces-

For bioenergy to contribute substantially to the energy mix, many technical, economic, environmental, commercialization, and policy issues must be addressed.

sary equipment and various tillage systems on soil quality. It may also be necessary to conduct this RD&D in parallel with study of adjoining land uses. This will improve understanding of the interaction of energy crops with the larger environment. Agreeing on what constitutes sustainability and means of realizing such systems are important issues.

- Agricultural chemicals. Research on the impact of agricultural chemicals on soil flora and fauna and on wildlife is needed. This includes research on the impacts on wildlife behavior and reproductive processes. Chemical pathways and fate need to be better understood, particularly when they affect more than the target species or move out of the target area. Understanding the dynamics of chemical use on energy crops, how to reduce movement of chemicals offsite, and how to reduce their use generally are important issues.
- Water quality. Research is needed on the impact of erosion/sedimentation and agricultural chemicals from energy crops, especially on riparian zones, and on the potential of various energy crops to serve as filters and buffers for riparian areas. Studies are also needed on how to best minimize potential leaching of agricultural chemicals into groundwater. Energy crops might be a useful tool for reducing nonpoint agricultural pollution, but data are needed to verify this and to provide better crop guidelines for realizing that end.
- Air quality. Research on the total fuel cycle emissions of various bioenergy crops, conversion, and end-use systems is needed in order to minimize air quality impacts. This includes better understanding of both rural and urban air quality issues and how to best trade them off to maximize benefits. Comparing the potential air quality impacts of bioenergy systems with those of a wide range of other fuel and energy technology options is a key issue.
- Habitat. Box 3-D listed a number of prototype guidelines for structuring energy crops in order to maximize their value as habitat, buffers, or corridors. Each of these prototype guidelines needs to be examined through extensive research in dedicated large-scale field trials and modified as necessary. Such research must consider the impacts of energy crops in the context of the regional landscape ecology and in the near- and long-term. Establishing overall goals for the desired habitat impacts—which species should be helped-of energy crops in the larger landscape will also require extensive analysis.
- Restoration of degraded soils and ecological functions. Energy crops may have the potential to reverse soil deterioration from human abuse in some cases. This might include improving problems of soil structure, loss of top soil or organic content, salinity, acidity or alkalinity, or even chemical or heavy metal pollution.[1] It might also include restoration of some water purification or wetland functions, including moderating flood damage. Research is needed to identify such opportunities, design systems to make best use of this potential, and verify performance in the field. Energy crop yields may be low on some of these lands, however, lowering the financial return to the land owner and discouraging such efforts. Means of overcoming such barriers may need to be explored.
- Greenhouse gases. The total fuel cycle (from crop production to end use) impacts of energy crops on greenhouse gases (including carbon dioxide, methane, isoprenes, nitrous oxide, etc.) needs to be evaluated for the various energy crops, conversion processes, and end uses. The development and use of a "minimum data set" of key emission factors would be useful for

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[1] Growing plants will take up a variety of chemical or heavy metal toxins, depending on the precise substance and the particular plant species. This poses a problem for food crops, as it concentrates the toxins and puts them into the food chain. In contrast, for energy crops these toxins may be removed in the energy conversion process (for example, destroyed by combustion or concentrated in the ash) and so may allow a gradual cleansing of the soil.

determining these impacts. Related effects such as on soil carbon balances or vehicle refilling station VOC emissions should be included. These fuel cycle emissions can then be compared for agricultural or energy crops and for fossil or biomass fuels.

- Crops and multiple cropping. The potential risks and impacts of various genetically modified energy crops will need to reexamined. A variety of multiple cropping systems should be evaluated to determine how to ensure soil quality, habitat benefits, crop productivity, crop disease resistance, and other key economic and environmental criteria. At the same time, research is needed to determine how to convert agricultural lands to tree crops and vice versa; the soils and microflora and fauna are often much different.

It must be noted, however, that such research is not being done in a vacuum. Extensive research has already been done or is underway for many of these and related topics in parallel systems and can be made use of here.[2]

In addition to these factors, designing energy crops to mitigate or provide these potential environmental costs or benefits may also impact other aspects of developing energy crops, particularly their economics. Each of these may need in-depth study.

Energy crops must be cost effective for producers and users. This will require a careful balancing of environmental considerations—including near-term local and long-term global environmental impacts—within the overall bioenergy economics. Detailed integrated analyses of the economics and environmental impacts of various bioenergy fuel cycles are needed. The potentially significant environmental services energy crops may offer may need some kind of recognition and valuation by society and landowners. This may be quite difficult.

As part of such an analysis, the habitat value of polycultures may need to be weighed against the difficulty of converting thereto fuels or electricity. For example, some polycultures may not be easily converted by current enzymatic hydrolysis processes to ethanol.[3] In the near term, it may be more important to verify the cost and performance of these conversion processes using R&D already in progress for narrowly specified (monoculture) feedstocks. For the longer term, it maybe useful to begin R&D now to adapt these enzymatic hydrolysis processes to mixed feedstocks as needed in order to increase habitat benefits. Some research on mixed feedstocks is underway at the National Renewable Energy Laboratory. It tends to focus, however—and rightly so at this early stage-on a few common farm species that might be mixed with the primary feedstock by accident rather than a much wider range of plants that might be considered on the basis of their habitat value.[4] Research into the conversion of feedstocks must be tightly coupled with field research on the habitat and other environmental benefits of particular combinations of crops.

To avoid disrupting key lifecycle processes for wildlife, biomass harvesting and other activities may need to be restricted during nesting and other critical times. This may require that sufficient biomass be stored to keep the conversion plant operating during this period; it may also require idling capital equipment used for harvesting and transport. Alternatively, electricity generation, for example, might be powered during such periods by the use of natural gas, and there maybe additional important synergisms between the use of

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[2] For example, the Electric Power Research Institute, the National Audubon Society, and others have initiated a National Biofuels Roundtable. This Roundtable is developing a framework for evaluating many environmental, socioeconomic, and policy issues associated with the development of bioenergy crops and conversion facilities.

[3] Under some conditions, polycultures may also contribute to slagging problems (the condensing of alkali metals on surfaces such as boiler walls, heat exchangers, etc.) in combustion equipment. Jane Turnbull, Electric Power Research Institute, personal communication, Aug. 31, 1993.

[4] Arthur Wiselogel, National Renewable Energy Laboratory, personal communication, Sept. 8, 1993.

biomass, natural gas, and renewable such as wind, photovoltaics, and solar therrnal.[5] On the other hand, a well established biomass industry may have a sufficient variety of crops and rotation cycles to moderate this disruption. Field trials are needed to determine the extent of these potential disruptions and means of moderating them.

Farm labor needs are largely determined by the intense effort required to plant and harvest conventional agricultural crops during a narrow window of time, usually spring and fall. Once planted, however, perennial herbaceous or woody energy crops may last 10 to 20 years, and harvesting may take place over a wide period of time. Adding such energy crops to the farmer's portfolio might then ease the burden during spring and fall, allowing better use of labor and capital equipment overall.

Bioenergy crops will also naturally move to their highest value use. This might be as a transport fuel, as a baseload backup to intermittent renewable, for industrial chemicals or fiber, or perhaps for environmental benefits. It will be useful to understand the full range of costs and benefits for each potential use of bioenergy crops, including budget and trade balance impacts.

These crops might best serve a variety of end uses simultaneously. In particular, the initial establishment of bioenergy crops might be assisted by coupling energy production with higher value uses of the feedstock. For example, an energy crop might be initially established to serve a higher value purpose such as the production of pulp and paper and only secondarily for energy. The experience gained through such partnerships may provide a foundation for further energy crop development and cost reductions.

Once a substantial market develops for low-quality wood fuels, there is the potential risk that will encourage owners to harvest low-quality timber that is serving as important wildlife habitat or to energy crop wetlands which are fertile but inappropriate for conventional agriculture. This is particularly important in regions such as the Northeast where forests are the primary biomass resource. Means of addressing such unintended side effects may be needed.

Increasing land-use constraints—environmental and other-on Federal lands may encourage pulp and paper and other biomass product users to move elsewhere. Competition for marginal and other lands may become more intense. At the same time, there maybe increasing land-use and environmental considerations for these agricultural or marginal lands. This may reduce the area available for energy crops. As noted above, however, combining multiple end uses such as pulp and paper with energy may assist the initial development and deployment of energy crops and their associated infrastructure.

The structure of the farm sector also plays a role in determining these environmental impacts and needs to be examined carefully. For example, roughly one-third of farms having fertilizer expenditures and one-quarter having pesticide expenditures in 1986 paid for some custom application procedures. Training such specialists in the timing and application of agricultural chemicals to minimize misapplication, potential groundwater leaching or runoff, or other problems may require one set of extension activities; reaching the two-thirds or more of farms which use on-farm hired laborers or do it themselves may require a different apreach.[6] Extension efforts will also vary between

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[5] See, U.S. Congress, Office of Technology Assessment, *Renewable Energy Technology: Research, Development, and Commercial Prospects,* forthcoming.

[6] New technologies may also help avoid some of these problems. For example, the development of time-release fertilizers (or other agricultural chemicals) would allow farmers to continue the common labor-saving practice of only spreading fertilizer (or other chemicals) once per year while reducing the amount that must be applied to ensure that the nutrients are available late in the growth cycle. See David O. Hall, Frank Rosillo-Calle, Robert H. Williams, and Jeremy Woods, "Biomass for Energy: Supply Prospects," Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams, (eds.), *Renewable Energy: Sources for Fuels and Electricity* (Washington, DC: Island Press, 1993).

Table 4-l—Distribution of Farms by Sales Class and Percent of Total Cash Receipts by Sales Class, 1987

Sales class	Value of farm products sold	Number of farms	Percent of all farms	Percent of total cash receipts
Small, part-time	<$20,000	1,380,000	63.4%	5.2%
Part-time	$20,000 to $99,999	495,000	22.8	17.3
Moderate	$100,000 to $249,999	201,000	9.2	22.0
Large	$250,000 to $499,999	71,000	3.2	22.0
Very large	***>$500,000***	***29,000***	1.3	**37.4**
Total	—	**2,176,000**	**100**	**100**

SOURCE: U.S. Congress, Office of Technology Assessment, *Beneath **The Bottom Line: Agrcultural Approaches to Reduce Agrichemical Contamination ofGroundwater,OTA-F-418*** (Washington, DC: U.S. Government Printing Office, November 1990).

the very large farms and the small, part-time farms (table 4-l). Tenants and part-owners are operating an increasing proportion of farms and farmland acres and may have less concern about environmental costs and benefits of various crops and management systems than owners.[7]

Finally, to realize the benefits of energy crops as habitat, buffers, and corridors may in some cases require a level of regional landscape planning not often seen in this country. This will require much more RD&D on regional landscape ecology and its sensitivity to imperfections. It will also require considerable effort in developing new policy instruments to encourage participation in forming such a landscape across many public and private properties. These issues are examined further below.

MARKETS AND BARRIERS

Agricultural production of energy crops faces a variety of market distortions and barriers that may slow their adoption. These will be discussed here within two broad categories: products and markets; and land use and rights issues. Many of the issues of commercializing alternative transport fuels themselves have been recently addressed in a separate OTA assessment,[8] particularly the difficulties inherent in developing a new fuel distribution infrastructure. The focus here instead will be on the difficulties in producing the crops.

Products and Markets[9]

The first difficulty faced by producers and converters of bioenergy crops is the chicken and egg problem of developing a market. To justify producing an energy crop, farmers must have a reasonably secure market for their product at a potentially economic price. On the other hand, electricity generators or liquid fuels producers need a reasonably assured and economic supply of biomass before they can justify building a conversion plant. For both parties, the economics of energy crops are improving but remain expensive.

Lead times to develop crops and conversion plants are also long. Typical SRWCs require 3 to 10 years to mature. Farmers are often reluctant to make the investment due to this long lead time and the need for interim cash flow, particularly with current low and uncertain prices for other forms of energy.

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[7] U.S. Congress, Office of Technology Assessment, *Beneath The Bottom Line: Agricultural Approaches to Reduce Agrichemical Contamination ofGroundwater,OTA-F-418* (Washington, DC: U.S. Government Printing Office, November 1990).

[8] U.S. Congress, Office of Technology Assessment, *Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles,* OTA-E-364 (Washington, DC: U.S. Government Printing Office, September 1990).

[9] The primary source for much of this section, which contains far more detail than presented here is: U.S. Congress, Office of Technology Assessment, *Beneath The Bottom Line: Agricultural Approaches to Reduce Agrichemical Contamination of Groundwater,* OTA-F-418 (Washington, DC: U.S. Government Printing Office, November 1990),

Energy crops may also reduce the flexibility of farmers. It maybe difficult to quickly plow under a tree crop and plant the land with something else should crop productivity, market conditions, or other factors limit the return on the farmer's investment of labor, land, and capital. Thus, while the Conservation Reserve Program encouraged U.S. farmers to convert 12 million hectares[10] of marginal cropland to permanent cover during 1986 to 1989, only 1 million hectares of this was planted with trees.[11]

Farmers typically make production decisions within short timeframes and with maximum flexibility, which discourages investments in potentially longer term and less flexible energy crops. Economic factors are typically the most pressing in farmer decisionmaking; market prices, support levels, credit availability, and debt load are critical considerations at the individual farm level. Farmers often are forced to make decisions within a short-term, year-to-year planning horizon that can prevent them from taking risks or making the most economically efficient decisions over a longer term. Farmers asked to respond voluntarily to public concerns about environmental impacts tend to evaluate proposed technologies, crops, management, or other aspects for their relative advantage within the existing set of economic conditions.

Many farmers also make changes slowly. Farm management changes, even relatively minor ones, are not decisions made overnight. Farmer adoption of relatively simple, highly profitable technologies such as hybrid com has taken as long as nine years on average. The decision to change farming practices requires a considerable degree of deliberation, and maintaining new practices frequently necessitates on-farm experimentation and adaptation beyond that conducted during initial technology development.

Farmers tend to underestimate the severity of environmental problems on their own farms. Farmers tend to perceive, for example, that soil erosion and water quality problems are more severe at the national level than they are in their own counties. They also tend to perceive these problems as least severe on their own farms. This "proximity effect" indicates that farmers are aware of the need to protect soil and water in general but often underestimate the need on their own farms. As a potential moderator of such environmental impacts under the right conditions, energy crops are therefore likely to be valued less than if the severity of these problems was fully appreciated.

Farmers are most likely to adopt technologies with certain characteristics. Favored technologies are those that: 1) have relative advantage over other technologies (e.g., lower costs or labor, higher yields, etc.); 2) are compatible with current management objectives and practices; 3) are easy to implement; 4) are capable of being observed or demonstrated; and 5) are capable of being adopted on an incremental or partial basis. Diffusion research indicates that farmers are probably more likely to test technologies or practices that they think have these characteristics. The complexity of systems-oriented changes will likely slow their adoption. This poses particular problems for regional landscape planning in order to maximize habitat benefits of energy crops. Mechanisms for incrementally realizing habitat benefits may be needed should these programs go forward.

Individual and farm characteristics appear to explain only a small portion of behavior associated with adopting new crops or farming practices; institutional factors (e.g., farm programs, credit availability, etc.) probably are highly influential. Research on individual farm characteristics (e.g.,

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[10] The total now stands at approximately 15 million hectares. Thyrele Robertson, U.S. Department of Agriculture, Soil Conservation Service, personal communication, Aug. 26, 1993.

[11] R. Neil Sampson, "Biomass Opportunities in the United States to Mitigate the Effects of Global warming," Donald L. Klass, (cd.), *Energy from Biomass and Wastes* XV (Chicago, IL: institute of Gas Technology, 1991).

size, specialization, land tenure) and farmer traits (e.g., age, education) and their relation to conservation adoption has yielded mixed results. Most researchers consider institutional factors to be much more influential, but few studies have been conducted on these to date. Studies on adoption of farm practices have also rarely examined the physical settings of adoption decisions or the extent of resource degradation as it relates to adoption of alternative farm practices.

Finally, farmers are a heterogeneous group with unequal abilities, unequal access to information and resources for decisionmaking, differences in willingness to take risks, and a wide range of objectives in even practicing farming. For example, farmers' objectives may include: making a satisfactory living (either as an owner-operator, tenant, or employee); keeping a farm in operation for family inheritance or other personal reasons, perhaps while working at an off-farm job; obtaining a satisfactory return on investments in land, labor, and equipment; obtaining tax benefits; obtaining recreation or esthetic enjoyment; and others. These objectives will influence the portfolio of crops, including energy crops, that a particular farmer will choose to grow.

Land Use and Rights

The potential habitat benefits of energy crops—as habitat, buffers, or corridors-will increase as they are integrated on a regional basis with the local ecology. Pursuing this to its maximum limit may require a degree of landscape planning that has rarely been seen in this country. This raises major issues in terms of land use and property rights, issues that are also at the center of controversies over the "Multiple Use, Sustainable Yield" philosophies of public lands management. These issues have been explored in depth in numerous publications and so will be only briefly mentioned here.[12]

Public and private properties already face a variety of environmental and other considerations in their use. These include zoning and land use planning, clean water and air laws, forest practice and pesticide control laws, endangered species laws, and a variety of other considerations. Whether and, if so, how such resource considerations might be extended to the production of energy crops will be a difficult but critical aspect of developing a bioenergy agenda.

Some of these controls maybe counterproductive if they are extended to bioenergy in an inflexible manner. For example, some argue that improving habitat on private lands may pose risks to property owners that if endangered or threatened wildlife establishes itself, the property owner will largely lose control of that land as well as on adjacent lands where activities might disrupt the wildlife.[13] As a consequence, anecdotal evidence indicates that some farmers may cut or bum potential habitat to prevent wildlife from using it; alternatively, the wildlife might simply be driven off or killed. Whether or not this is a significant problem or how widespread the problem might be is unknown. Using energy crops as habitat, buffers, or corridors will require understanding and carefully addressing these issues.

These issues thus address fundamental assumptions and values of, for example: what actually is private property (e.g., what is really owned?); to what extent can a person use or abuse private property and at what point do larger community interests become important; how does one value different environmental goods and services—including clean air and water, quality soils, wildlife, and aesthetics—and how can that be translated into functioning markets; and how does one determine and apply discount rates, if at all, to natural

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[12] See, for example: Congressional Research *Service, Multiple Use and Sustained Yield: Changing Philosophies for Federal Land Management?* Workshop Proceedings and Summary, Mar. 5-6, 1992, Committee on Interior and Insular Affairs, U.S. House of Representatives, Committee Print No. 11, December 1992.

[13] John Miller, "Land of the Free: An Environmental Strategy for Republicans," *Policy Review,* Winter 1993, pp. *66-70.*

resources? These issues pose substantial challenges to public policy.

CLOSE

Energy crops can potentially help meet a number of national goals, including: national energy and security needs, improving the trade balance, reducing Federal budget deficits, stimulating rural economic development, and improving the environment. Realizing this potential will require a long, dedicated effort in terms of research, development, demonstration, and commercialization of these technologies. Haphazardly implementing large-scale bioenergy programs without such a foundation could damage the environment and reduce potential economic benefits.

Appendix A: Related OTA Studies

OTA has previously published a number of studies addressing issues related to energy crops and their environmental impacts. Previous studies include the following:

- U.S. Congress, Office of Technology Assessment, *Impacts* ***of Technology on U.S. Cropland and Rangeland Productivity*** OTA-F-166 (Washington, DC: U.S. Government Printing Office, August, 1982)
- U.S. Congress, Office of Technology Assessment, ***Beneath the Bottom Line: Agricultural Approaches to Reduce Agrichemical Contamination of Groundwater, OTA-F-418*** (Washington, DC: U.S. Government Printing Office, November 1990).
- U.S. Congress, Office of Technology Assessment, ***Energy from Biological Processes, OTA-E-124*** (Washington, DC: U.S. Government Printing Office, July 1980), ***Volume II, Volume III-Appendixes OTA-E-128*** (September 1980).
- U.S. Congress, Office of Technology Assessment, ***Water-Related Technologies for Sustainable Agriculture in U.S. Arid/Semiarid Lands, OTA-F-212*** (Washington, DC: U.S. Government Printing Office, October 1983).
- U.S. Congress, Office of Technology Assessment, ***Forest Service Planning: Setting Strategic Direction Under RPA,*** OTA-F-441 (Washington, DC: U.S. Government Printing Office, July 1990).
- U.S. Congress, Office of Technology Assessment, ***Forest Service Planning: Accommodating Uses, Producing Outputs, and Sustaining Ecosystems, OTA-F-505*** (Washington, DC: U.S. Government Printing Office, February 1992).
- U.S. Congress, Office of Technology Assessment, ***Technologies to Maintain Biological Diversity, OTA-F-330*** (Washington, DC: U.S. Government Printing 0ffice, March 1987).
- U.S. Congress, Office of Technology Assessment, ***Technologies to Benefit Agriculture and Wildlife, Workshop Proceedings, OTA-BP-F-34 (Washington,*** DC: U.S. Government Printing Office, May 1985).
- U.S. Congress, Office of Technology Assessment, ***Changing by Degrees: Steps to Reduce Greenhouse Gases, OTA-O482*** (Washington, DC: U.S. Government Printing Office, February 1991).

Appendix B: Units and Conversion Factors

Conversion Factors

Area

1 square kilometer (km^{2})=
0.386 square mile
247 acres
100 hectares
1 square mile=
2.59 square kilometers (km^{2})
$6.4x10^{2}$ acres
$2.59x10^{2}$ hectares

1 acre=
0.405 hectare (ha)
$1.56x10^{-3}$ square miles
$4.05x10^{-3}$ square kilometers (km^{2})
1 *hectare=*
0.01 square kilometer (km^{2})
$3.86x10^{-3}$ square miles
2.47 acres

Weight

1 ***kilogram (kg)=***
2.20 pounds (lb)
1 pound (lb)=
0.454 kilogram (kg)

I metric tonne (mt or “long ton”)=
1,000 kilograms or 2,200 lbs
1 ***short ton=***
2,000 pounds or 907 kg

Energy

1 quad (quadrillion Btu)=
$1.05x10^{18}$ Joules (J)
1.05 exajoules (EJ)
$4.20x10^{7}$ metric tonnes, coal
$1.72x10^{8}$ barrels, oil
$2.34x10^{7}$ metric tonnes, oil
2.56x101° cubic meters, gas
$5.8x10^{7}$ metric tonnes dry wood
$2.92x10^{11}$ kilowatthours

1 ***kilowatthour=***
$3.41x10^{3}$ British thermal units (Btu)
$3.6x10^{6}$ Joules (J)
1 ***Joule=***
$9.48x10^{-4}$ British thermal unit (Btu)
$2.78x10^{-7}$ kilowatthours (kWh)
1 ***British thermal unit (Btu)=***
$2.93x10^{4}$ **kilowatthours (kWh)**
$1.05x10^{3}$ Joules (J)

Volume

- ***1 liter (1)=***
  - ***$2.64x10^{-1}$*** gallons (liquid, U. S.)
  - $6.29x10^{3}$ barrels (petroleum, U. S.)
  - $1x10^{-3}$ cubic meters (ins)
  - $3.53x10-^{2}$ cubic feet (fi^{3})
- 1 ***gallon (liquid, U.S.)=***
  - ***3.78*** liters (1)
  - $2.38x10^{-2}$ barrels (petroleum, U. S.)
  - $3.78x10^{3}$ cubic meter (m^{3})
  - $1.33x10^{-1}$ cubic feet (ft^{3})
- 1 ***barrel (bbl) {petroleum, U.S.)=***
  - ***$1.59x10^{2}$*** liters (1)
  - ***42*** gallons (liquid, U.S.)
  - $1.59x10^{-1}$ cubic meters (m^{3})
  - 5.61 cubic feet (ft^{3})
- **1** ***cubic meter (3)=***
  - $1x10^{3}$ liters (1)
  - $2.64x10^{2}$ gallons (liquid, U. S.)
  - 6.29 barrels (petroleum, U. S.)
  - 35.3 cubic feet (ft^{3})
- ***1 cubic foot (ft^{3})=***
  - ***$2.83x10^{1}$*** liters (1)
  - 7.48 gallons (liquid, U. S.)
  - $1.78x10^{-1}$ barrels (petroleum, U. S.)
  - $2.83x10^{-2}$ cubic meters (m^{3})
- 1 ***cord wood=***
  - 128 cubic feet (ft^{3}) stacked wood
  - 3.62 cubic meters (m^{3}) stacked wood

Temperature

From Centigrade to Fahrenheit:
((9/5) x ***(“C))+ 32 =^{o}F***

From Fahrenheit to Centigrade:
(5/9) x (^{O}F - 32) -‘C

Temperature changes:

—To convert a Centigrade change to a Fahrenheit change:
9/5 x (change in ‘C) = change in ‘F
—To convert a Fahrenheit change to a Centigrade change:
5/9 x (change in oF) = change in ‘C
—Example: a 3.0‘C rise in temperature = a 5.4‘F rise in temperature

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