Potential Environmental Impacts

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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 substantial] y offset these benefits and 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.

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

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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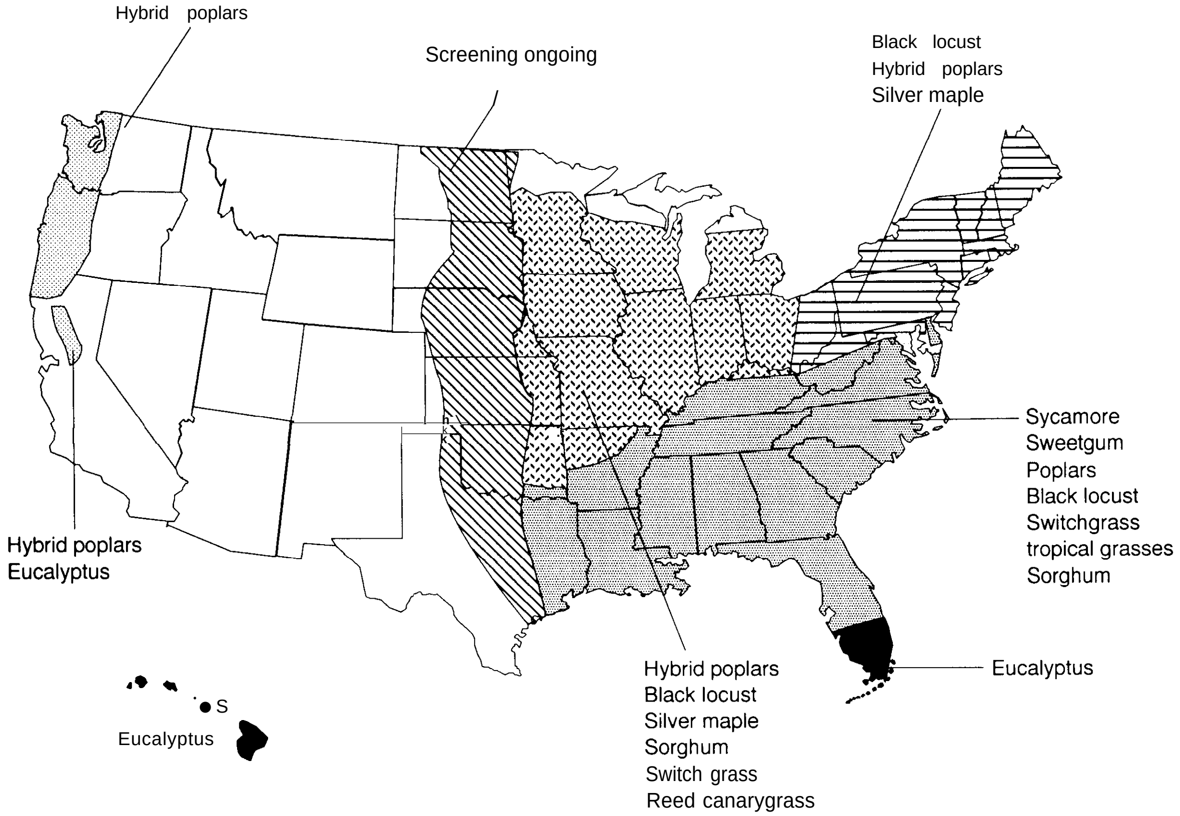
[1] Defining "natural habitat" may be difficult and controversial because past decades—sometimes centuries—of clear cutting, selective harvesting of economically valuable trees, and fire suppression have altered many U.S. forests, often leading to an increased concentration of plant species with lower 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-l—Typical Erosion Levels and Agricultural Chemical Use of Selected Food and Energy Crops

		Fertilizers			
Crop	Erosion (Mg/ha-yr)	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 pre-agricultural 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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[9] 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] T. serve as a filter and t. 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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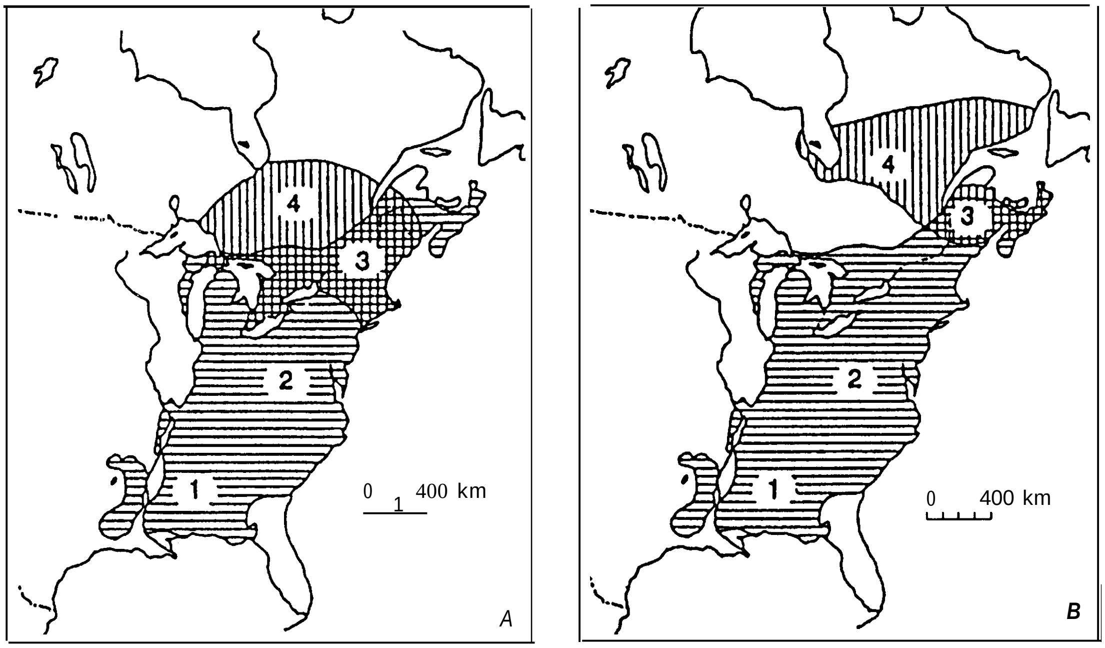
[56] Douglas A. Thompson and Thomas G. Yocom, "Uncertain Ground," *Technology Review,* August/September 1993, pp. *20-29.*

[57] J David A] Ian 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, *Jn.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 t. 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_20, 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.

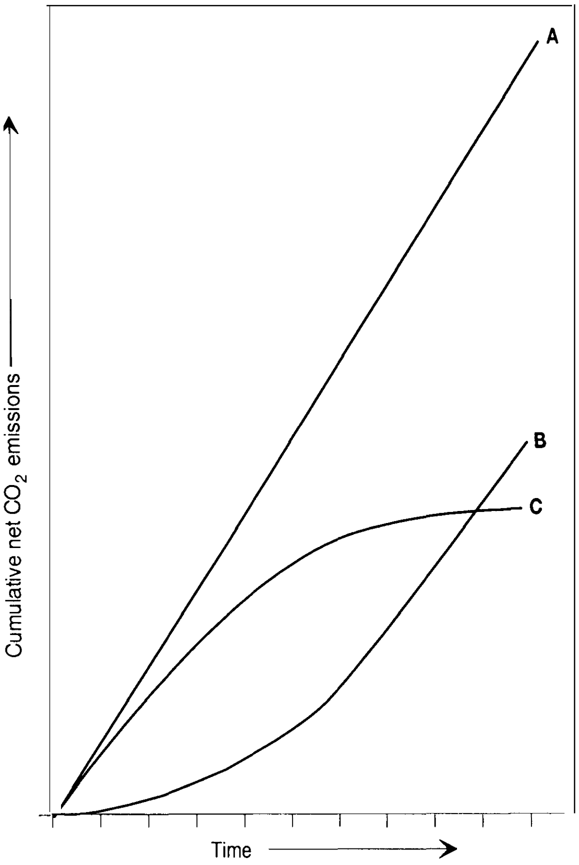
[87] L L Wright and E.E. Hughes, "U.S. Carbon Offset Potential Using Biomass Energy Systems," *Journal of Water, Air and Soil Pollution*, in press. See also footnote 81.

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.