Biotechnological Advances in Biomass Energy and Chemical Production: Impacts on Wildlife and Habitat

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ABSTRACT

One promising application of biotechnology is in making the production of energy and chemical products from plants ("biomass") practical. Applications include new markets for crops and reduction of wastes by using field residues or "wastelands" as feedstocks in biomass energy production. In addition, engineered crops could synthesize complex compounds. However, conversion to widespread use of biomass could have undesirable impacts. For example, changes in cropping practices may reduce wildlife populations or disrupt food chains. Other negative impacts of an environmentally insensitive development might include increased release of CO_2 (worsening global warming), and production of wastes, either water, chemical or biological, that present disposal problems. Biotechnology applied to biomass and chemical production has the potential for aiding economic development while greatly improving environmental quality. Environmental concerns are expressed in this paper, in the belief that consideration of potential problems at the inception of a technology increases the likelihood that environmentally sound courses will be pursued.

I. INTRODUCTION

It is a commonly repeated truism that the world's reserves of oil and natural gas are finite. It will eventually be necessary to convert to other raw materials to supply the primary sources for motor fuel, plastics, and industrial chemicals. Coal and/or biomass (fresh plant or animal material) are the logical raw materials that could become a substitute for oil and gas. Although finite in amount, the world's coal reserves, particularly those which lie deep underground, are likely to last for hundreds of years at today's rate of energy consumption.[1] This is why coal has typically been the long-term fuel of choice among technologists. However, given the rapid advances that have been made in biotechnology recently, it is possible that the most efficient, cheapest, and cleanest substitutes for fuel and petrochemicals may come not from converted coal, but from genetically engineered biomass, particularly in the form of crop plants and trees. Moreover, the U.S. Environmental Protection Agency, in its draft report to Congress, "Policy Options for Stabilizing Global Climate," projects that biomass energy could eventually become the world's largest single energy source following intervention to protect the climate.[2]

A. Biomass: the Possibilities

In light of such projections, and considering the potential of new applications in biotechnology, the environmental consequences of converting to large-scale use of biomass for fuel and feedstocks must be evaluated, particularly when such a switch might affect large areas of land. In assessing what the ecological effects could be if biomass production was expanded to suit future fuel and chemical needs, the market demand and economic potential for supplying biomass-derived compounds must be considered. Future demand for biomass products will depend on a great many factors, including public concern about traditional fuel sources exacerbating global climate problems, availability of cheaper fuel, and technological advances in alternative energy sources. Perhaps the greatest determining factor will be the cost of future biomass-derived fuel and chemicals, which is why technological advances in biotechnology will be intimately related to the widespread penetration of biomass technology into the $440 billion per year U.S. energy market.[3] Certainly there will be some uses of biomass that will not gain from biotechnological advances in production and processing, but the responsibility for turning this technology into a major replacement for fossil fuels will more than likely lie with genetic engineering.

Should biotechnology make biomass production processes economically viable by lowering costs, or should concerns about global warming rule out synthesizing transportation fuels from coal, biotechnologically enhanced biomass-for-energy products, such as ethanol, could become the major source of transportation fuel in the U.S. Such dominance is not expected for sectors other than transportation, such as the electricity sector, where there are alternative sources with both low global-warming impacts and good technological prospects for reduced cost. Electricity producing solar cells are an example: although biomass has advantages when it comes to energy storage, solar collection by solar cells are an order of magnitude greater in efficiency than that by biomass.[4] Only in the transportation sector, where electricity has difficulty competing, is the field wide open for biomass-based alcohol production.

In addition to fuel, as fossil hydrocarbon prices rise, genetically engineered biomass could also substitute for petrochemicals currently used to manufacture plastics and an array of biochemical products.[5] Products so far seen as feasible to manufacture from biomass include a variety of alcohols, sugars, organic acids such as fatty acids, and esters.[6,7] (see Table 1). Compounds that are currently difficult to synthesize or

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Table 1
Examples of Proteins Whose Genes Can be Transferred Between Species[7,16,30,86,101]

Blood Proteins	
Antithrombin III	
Fibrinogen	
Plasmin	
Serum albumin	
Streptokinase	
Thrombin	
Urokinase	
Digestive Enzymes	
Amylase	
Chymotrypsin	
Pepsin	
Trypsin	
Other Enzymes	
Collaginase	
Dextranase	
Lysozyme	
Nucleases	
Enzymes that confer herbicide resistance	
Hormones	
Angiogenin	
Insulin	
Somatotrophins	
Thyroid hormones	
Immunoglobins	
Interferons	
Toxins	
Bee venom	
Endotoxin of *Bacillus thuringiensis*	
Snake venom	
Viral Coat Proteins	
Tobacco mosaic virus	
Potato virus X	

Note: Current examples are mainly human proteins, because the technology is much farther advanced in this than in other areas.

purify chemically, such as amino acids, are products that offer some promise for the biomass industry.

For biomass to become a major source for plastics and specialty chemicals, either the feedstocks used must be cheap, or the products must be highly valuable. Limitations on current biotechnology for high-volume chemicals are discussed by Goldstein[6] and Drozd.[8] Any progress with genetic engineering that employs cheaper feedstocks or produces more valuable products can be expected to have dramatic effects on the chemical industry.[6,9,10]

B. Environmental Considerations of Converting to a Biomass-Driven Economy

Environmental concerns associated with biomass production for fuel or feedstock markets include air and water quality, appropriate waste disposal, minimizing roads in wild areas, and competing uses of the land for biomass production with land needed for other commercial purposes.[11,12] Although we consider some of these topics below, we focus on issues related to protection of wildlife habitat and lands with special qualities.

Biomass technology clearly offers great promise. Tailoring the genetic substance of plants and microorganisms to better serve as raw material for fuel and/or chemicals may offer relief from energy shortages, air pollution, and global warming. The potential is there to develop a clean and healthy technology that provides products important to the quality of life.

Most environmental problems are a result of an inadvertent lack of consideration for natural cycles, wildlife biology, ecological processes, and the history of past environmental problems. If engineers who design chemical and biochemical processes either collaborated more extensively with ecologists, or were more familiar with the ways in which natural systems can be negatively altered, they would be better able to anticipate and design solutions to many would-be environmental problems. We feel that a major strategy for guiding environmental protection in biotechnology should be to acquaint biotechnologists with the problems that are likely to arise. This paper is an introduction to the subject, one which will hopefully encourage biotechnology energy companies to fully integrate ecologists and environmentalists into their planning.

Some potential environmental problems using biomass as feedstock for energy or chemical products are listed below:

1. Pressures for competing uses of a finite amount of land. An increase in demand for biomass products would intensify pressure to convert currently uncultivated land, such as forest and rangeland, to biomass farming.
2. Exacerbation of global climate problems, should commercial biomass be grown on a nonsustainable basis or replace natural ecosystems with crops which store less carbon.
3. Pollution of the environment from waste products of the biomass industry.
4. Declines in wildlife if grazing lands, croplands, and commercial forests are supplanted by expanded agriculture and silviculture for biomass production.
5. Destruction of what some look upon as "wastelands": wetlands, deserts, riparian areas, and noncommercial for-

ests. Currently, these lands are not used principally for economic purposes and, therefore, are the last vestiges of prime wildlife habitat outside of state and federally protected lands. If, in the future, they become economically viable for biomass production, the wild species they support will likely decline dramatically.

6. Spread of genetically engineered organisms to unintended locations, where they may become pests or destroy the integrity of parks, wildlife refuges, and wilderness areas.

In this article, we consider the prospects for biomass production and its potential effects on land use in light of the likely ability of biotechnologists to design plants and microorganisms to meet the demands of highly technological societies. With the exception of number 6 above, we do not focus on traditional environmental concerns related to inadvertent escape or undesirable transformations of genetically engineered organisms (engineering failures); rather, we look at environmental side effects that may result from successful application of technological techniques to the large energy and chemicals market. We chiefly consider the ecological advantages and disadvantages of biomass production in relation to land use changes that could result in the U.S. Relevant economic factors are mentioned but not analyzed. Social consequences are important as well, but are outside the scope of this paper.

II. WHAT BIOTECHNOLOGY CAN DO

Energy from biomass has been proposed since before the energy crises of the 1970s; it was then that Brazil converted its domestic transportation systems to biomass-based ethanol. Generally speaking, though, there has not been a widespread acceptance of using biomass energy products. The main reason for this is economic: currently, traditional fuels are, for a number of reasons, cheaper.

Biotechnology in its broadest sense is merely applied biology. Currently, the term is associated with the application of novel approaches to economically important problems. The most radical of the new technologies is genetic engineering. Using genetic engineering, rapid improvements in plant and animal performance are possible, and the conversion of animal waste products into chemical feedstocks or synthesis of drugs such as insulin by common bacteria become viable options.[13-17]

Other, less spectacular forms of biotechnology are also having revolutionary impact. In particular, improvements in cell and tissue culture are enabling plant and animal breeders to cut weeks or years out of the time needed to develop new varieties.[10,18,19] The net result is that striking progress has been made in a few years, revitalizing a number of industries.

While increased environmental awareness might have renewed interest in energy from biomass without the benefit of biotechnology, biotechnology promises solutions to some of the steps that kept biomass energy from becoming economically viable.[20] There is a consensus among plant biologists that by modifying plant characteristics, biotechnology will be able to improve the quality of biomass materials that are used to produce fuel or chemicals.[21,22] Should these promises be kept, we expect biomass energy will compete effectively with other sources of energy. It is the environmental consequences of such successes that concern us.

One of the most significant impacts biotechnology could have on biomass energy production is the reduction of costs, by virtue of formulating faster, more efficient enzymes, and by economically enabling previously inert molecules such as cellulose to be broken down.[20,23,24] Biotechnology's chief contribution to biomass energy production will most likely be in improving processing methods by increasing the efficiency of the organic enzymes used, or of the organisms that carry out the reaction sequence.[23] Biotechnology may also help to reduce the volume and toxicity[25-27] of the waste generated from biomass production technologies that use fossil fuel.

Current methods of biotechnology allow for the transference of single genes from plants, animals, and microorganisms into other organisms of the same. The methods have advanced to the point that proteins that are produced in a single step can be introduced into other species. For example, the gene for the insect-killing toxin of the bacterium *Bacillus thuringiensis* has been inserted into the tissues of tomato plants so that the toxin is produced by the plant tissues.[13] Bioengineering cannot be applied to all plants at this point in the research and development stage, but progress is rapid, and it is expected that most if not all plants should be amenable to recombinant DNA techniques within a decade.[14,16,18] Many biological compounds are already being produced commercially in alien organisms. For example, insulin for human diabetes, and bovine somatotropin produced in bacteria *(Escherischia coli)* are being commercially produced.[17]

To date, successful products of genetic engineering are proteins. Although proteins are often catalysts in the synthesis of other molecules, there are limitations; it is impossible to synthesize just any chemical in this way. Table 1 lists representative protein products that existing technology can use. Many of the products that chemical industries use and develop (see Table 2) currently are not amenable to genetic engineering. Many chemicals, such as fats, sugars, and starches, cannot be made by engineered organisms because these chemicals are made by the action of a sequence of specific enzymes, and coordinate transfer of multiple genes is not currently possible.

If a desired compound occurs in higher plants, but cannot readily be synthesized by engineered organisms that can be grown in vats (see below), one alternative is to increase the production rate of the desired chemical within plants. A variety of methods exist for enhancing the amount of compound a plant produces, including selection for improved promoter genes (which regulate the rate of synthesis), removal of genes that

Table 2
Chemicals Targeted for Biotechnological Improvements in Biomass Production and Processing Methods[9,15,54,55,86,102,103]

- Acetone
- Butylene glycol
- Ethyl acetate
- Formaldehyde
- Glycerine
- Glycerol
- Lactones
- Methane
- Alcohols
  - Ethanol
  - Methanol
  - Butanol
  - Plasticizer alcohols (C_6-C_8)
  - Detergent alcohols (C_{10}-C_{18})
  - Xylitol
  - Sorbitol
- Acids
  - Acetic acid
  - Acrylic acid
  - Amino acid
  - Citric acid
  - Fumaric acid
  - Levulinic acid
- Cellulosics
- Drugs
  - Cardiac glycosides
  - Morphine alkaloids
  - Shikonins
  - Tropane alkaloids
- Enzymes
- Essential oils
- Microbial polysaccharides
  - e.g., xanthan gum
- Polyesters
- Starch derivatives
- Vitamins

inhibit production, and insertion of multiple copies of the particular gene.[28] While producing the compound in cells throughout the plant should result in the greatest yield, even if tissue specificity is required for ease of harvest or to reduce toxicity to the plant itself, substantial amounts of organic compounds could be produced in this way.[10]

In the future, naturally occurring and fabricated compounds[15,17,21] could be produced in biological systems vastly different from the ones in which the compounds originally evolved. Whether this has practical applications for commercial enterprises and is not simply an academic curiosity will depend on how economical the production processes become and the inherent technological and sociological value of the products. Certainly, decreasing petroleum resources and the rising costs of petrochemicals will be a driving force behind making biotechnology an important industry. In fact, improvements in biotechnology are expected to make biomass technology very important to many industries early in the next century.[19,29]

III. SOURCES FOR BIOMASS PRODUCTION: METHODS AND ENVIRONMENTAL IMPLICATIONS

Biomass is the term for biologically produced matter of any sort.[30] Biomass may be grown specifically for the product as herbaceous or woody matter, or the biomass may be supplied from the wastes of agriculture, forest, or industrial products. In the context of energy and chemical production, biological material — usually plants or agricultural byproducts — is used as starting material for a number of uses: to generate electricity, for fermentation products such as alcohol or natural gas,[31] and manufacturing chemicals.[32]

Genetic engineering of biomass proteins or enzymes can be applied to a variety of production processes, including agriculture/silviculture, aquatic cultivation, and vat production. The different production methods in which genetic engineering of biomass is likely to be employed are briefly described below.

Also discussed are some of the associated environmental problems that could arise. Impacts on wildlife and habitat could either be positive or negative, depending on the size of the markets and on the technological choices that are made. If biotechnology should be restricted to food crops alone, it is possible that increases in productivity could free up agricultural land for uses that will improve habitat. Similarly, should fast-rotation woody and herbaceous crops simply displace food crops, there would also be some improvement in habitat. On the other hand, should markets be large, and biomass crops spread into land with superior habitat, the impacts on wildlife could be very negative, unless careful attention is paid to preserving biodiversity. Clearly, it would be wise public policy to be prepared for either of these situations.

A. Agricultural/Silvicultural Production of Biomass for Fuel or Chemical Feedstocks

Many important industrial processes require ethanol or other products that can be produced by fermentation of whole plants (see potential products section following). Any plant might work, although some are better than others. Land plants can be derived in either of two ways: by growing the crop specifically for biomass production, thereby using all the biomass, or by using crop wastes left after harvest. While in the first case the yield is much greater, biomass production may compete with land used for production of food or fiber crops. If crop wastes are used to supply the biomass material for fuel or chemicals, there is no loss of cropland for food or fiber, but removal of such wastes, if carried to extremes, can seriously reduce soil fertility, and food and cover for wildlife species. Nevertheless, there are suitable circumstances for using dedicated cultivation of biomass and for using crop wastes.

Forest lands may also be affected by markets for biomass. Trees may become an important source of biomass as a feedstock. At present, trees are virtually unchanged from their wild progenitors and are not as productive as corn and other row crops. However, biotechnology is expected to be revolutional in improving trees as sources for a variety of feedstocks.[33,34] Wood industry byproducts already provide a source of biomass.[21,35,36,37] Using forests, or more realistically, young second growth trees, as biomass is certainly feasible should the end-products come into demand. Pilot projects for biomass tree-farming have so far not been economically profitable enough to encourage large-scale production.[35] Tailoring the genetic makeup of specific tree species to suit commercial needs and improving management and harvesting methods could make such an industry economically viable. However, even if biotechnology were successful at improving crop yields on range and forest lands, it is hard to imagine average annual yields exceeding 10 dry metric tons/ha/yr on a wide scale. Short-rotation intensive culture of hardwoods has resulted in improved productivity, but at current levels of technology, it remains limited by site quality.[35,38,39]

1. Biomass Cultivation

Biotechnology, combined with traditional breeding, is expected to significantly enhance plant productivity. For little-studied species, such as cattails and poplars, traditional plant breeding should produce definite improvements in productivity.[40] As genetic engineering progresses, it too will contribute to plant improvement. Crops that are relatively well studied genetically, such as maize, can be readily tailored for large-scale biomass production. However, given the number of variables that will determine how extensively crops will be raised solely for biomass, it is difficult to accurately predict the degree to which biotechnology will be applied to improve biomass production.

In general, a variety of plants has been suggested as biomass crops for conversion to fuel or chemical feedstocks. However, many are currently restricted to specific geographic areas or are of limited use due to the intensity with which the crop must be managed.[41,42] Some source plants that have been suggested for biomass include cattails (*Typha* spp.),[43,44] water hyacinth *(Eichhornia crassipes)*,[45] sorghum *(Sorghum bicolor)*,[46,47] sugar cane (*Saccharum* spp.),[47] corn *(Zea mays)*,[48] and fast-growing trees such as *Populus* and *Eucalyptus*.[35]

Land for biomass production is likely to be in short supply if a significant percentage of energy demand is to be met (see *Markets and Influence on Land Use,* Section IV, below). Where water is limiting and irrigation technology can be economically applied, most land is irrigated for crop production, whether it is corn in Nebraska, rice in California, or sugarcane in Florida. In general, woody biomass requires as much or more water than herbaceous biomass. Terrestrial biomass production currently requires large amounts of water, much more than is required to produce synthetic fuels from coal,[49] and diversion of streams or rivers produce a host of ecological consequences.[50] Because even plants for biomass that are genetically engineered to be drought resistant will require some water, providing adequate water for all users may be one of the most difficult environmental problems to solve.

It seems unlikely that the biomass market will be valuable enough to displace irrigated crop production. However, salinization has reduced or prevented agriculture on at least 50 million ha of agricultural land.[51] Genetically manipulating plants to make them salt tolerant could enable some, if not all, of this degraded agricultural land to be put back into high production for biomass fuel or feedstocks.

Higher agricultural productivity will probably mean greater consumption of nutrients. This can cause rapid soil depletion. While replacing lost nutrients via fertilizer is a normal agricultural practice, fertilization is nevertheless an additional cost of this technology. For forests and rangelands (see below), replacing consumed nutrients by fertilization represents a novel disturbance, and one that is likely to displace some species. One proposed use of genetic engineering is to increase plant nutrient efficiency, or the efficiency of symbiotic associations that provide the nutrients.[52] Thus, the drains of nutrients that result from more intense use could potentially be ameliorated by biotechnology, which undoubtedly would be an important benefit.

More productive crop plants, especially those engineered to require minimal postharvest processing, are also likely to be more susceptible to pests. Through genetic engineering, pest-resistant traits are being introduced, but often these plants are less productive than the unengineered (and unprotected) varieties.[13] Thus, expanded application of biocides may be needed to protect these varieties. Contamination of soil and water by pesticide residues is already a major problem;[53] any technology that expanded it would worsen pollution problems that have already reached unmanageable proportions. Plans to use biological protection are admirable; we hope that the ecological benefits will provide incentive for researchers and policymakers to work such environmental safety measures into research and management schemes.

Another risk of biotechnology is the potential spread of life-forms, be they microorganisms or plants, that may take hold in ecosystems where they are not wanted.[54] Fast-growing trees for biomass may invade other ecosystems, at potentially great costs. The introduced trees *Melaleuca* and *Schinus* in Florida are changing the very nature of the plant communities there.[55] Kudzu vine, introduced to the southern U.S. to control erosion in the 1930s, has expanded well beyond its intended range and the plant communities under a kudzu canopy are greatly altered as a result.[56] Such impacts will similarly be possible as a result of genetically engineering biomass crops. In addition, many microorganisms used in biotechnology are themselves plant pathogens, and should be managed with care.[57]

While the potential power of genetic engineering to produce tenacious organisms raises concerns about their spread,[54,58-60] this technology also has the power to engineer into these organisms a weakness, an "Achilles heel" or a "suicide gene",[61] which may offer control should they spread to unintended locations, such as forests, national parks, or wildlife refuges. If we have the foresight to research such techniques and apply them if they turn out to be successful, these genetically engineered products could present less of a risk than what is experienced when natural organisms are transplanted across ecosystem boundaries. On the other hand, such technological fixes should not serve as an excuse for avoiding ecological analysis prior to introducing novel organisms.

a. ECOLOGICAL EFFECTS OF CONVERTING TRADITIONAL CROPLAND TO CULTIVATED BIOMASS FOR FUEL OR FEEDSTOCK PRODUCTS

If market forces encourage biomass production, cultivated land used for biomass production could come to compete with existing crops for space. In a time of surplus grain, shifting to biomass crops would seem an attractive approach. The problem is that with a growing world population, overproduction of food will not continue indefinitely. Ultimately, we expect conflicts between using land for food and for biomass. To avoid such competition and still accommodate for the expansion of biomass production, new lands will have to be brought into cultivation. Plowing land to grow plants for biomass significantly modifies, if not eliminates, the uses of the unplowed land. Even if land is not plowed but only harvested as bulk photosynthate for biomass production, this will radically change its animal and plant communities. A disturbed area mowed for biomass may regenerate much of the plant community within a year, but is not likely to maintain the same species distribution as existed prior to disturbance.

Regardless of how intensively areas are managed, the cultivation of currently unplowed lands will cause animal populations to decline in number and diversity; however, the degree of management will determine the extent to which this happens. Cultivated croplands that require intensive management, such as fruit and vegetable farming, do not typically support many animals, either in number or diversity.[50] Despite its managed nature, most cropland nevertheless does provide at least some wildlife habitat. Determining how such habitat can continue to support wild species, and integrating these ecological components into biomass technology is of primary importance if the industry is to be sustainable.

Another typical concern of agricultural engineers is crop damage by wild animals. Should biomass technology lead to the penetration of agriculture into new areas, wildlife populations that are encroached upon are likely to be viewed as expendable pests by the new users. Given historical trends in controlling animal damage, future biomass farming could lead to pressure to reduce animal populations that would have otherwise been ignored.

Diversity in crop planting provides some diversity of habitat. It would not be unreasonable to use habitat for wildlife as a criterion in choosing what crops to plant where. Although diversity is generally thought to run counter to economic efficiency, that is by no means always the case,[62] and perhaps genetic engineering techniques can offer further alternatives. Indeed, biomass plants could be bio-engineered to provide a diversity of habitat if tailored to be high yielding when used under intercropping conditions.

CO_2 and Potential Climate Problems — Improper use of biomass for commerical purposes could exacerbate global climate problems, especially if it is grown on a nonsustainable basis or without regard to natural cycles. For instance, if a forest is cut down to grow crops or small trees, there will be a one-time net addition of carbon dioxide to the atmosphere, including loss of soil carbon.[63,64] On the other hand, if biomass crops are grown sustainably using current row cropland, biomass production will not increase the net amount of carbon dioxide in the atmosphere (unless fossil fuels are used for fertilizer or to harvest and transport the crops to markets). And should biotechnological improvements allow significant amounts of crops for biomass to be grown on land with carbon-depleted soils, good management could lead to a net removal of carbon from the atmosphere by locking up more carbon in the soil.

Although using biomass-derived fuel is likely to add lesser amounts of trace gases to the atmosphere over the long term than the consumption of an equivalent amount of coal or other fossil fuel, attention to net carbon storage and release will be important in maximizing the benefits of increased use of biomass without exacerbating existing problems.

b. ECOLOGICAL EFFECTS OF BIOMASS FARMING ON CURRENTLY FORESTED LAND

The U.S. has 735 million acres (300 million ha) of forests (i.e., land with an excess of 10% tree cover).[65] Of this, 75% is commercial land and privately owned.[65] Most of the remainder lies in national forests. Here, tree harvesting is often allowed, although wildlife values are supposed to be given equal weight.[65] There is great natural diversity within forests: 156 varieties of forest are recognized in the continental U.S. alone and these forest communities support 1500 vertebrate species, and even more invertebrate species.[65]

There are two chief concerns about the impact of biomass technology on forests. First, forests may be converted to cropland in order to grow biomass crops. Second, forested lands may become intensively managed farms of genetically engineered tree species to produce biomass feedstocks. At a minimum, these trends can be seen as leading toward less diverse ecosystems as a result of both the uniformity of human-managed landscapes (especially the preference for crops in monoculture), and because only a few organisms can survive the recurrent disturbance inherent in planting annual crops or harvesting rapidly growing forests.

For forests to be maintained as quality habitat for wildlife, it is crucial that there be variety among and within ecosystems; spatial diversity — vertically and horizontally — is essential as well as is diversity in age distribution.[65] Because such variety is deliberately eliminated from commercial forests, they tend to support fewer animals, in number and diversity, than do unmanaged forests.[65] Should biotechnology lead to the expansion of land under silvicultural production, wildlife dependent on those original wild or semiwild lands would be expected to decline.

Land currently under natural forest cover has not been converted to agricultural land primarily because it could not profitably be farmed. Only rarely have forests been left where the land was considered arable,[50,66] although in some areas, such as the Northeast, an increasing number of small, secondary forests are grown for aesthetic purposes. Most forests in the U.S., currently on lands that are not suitable for cultivation — specifically those on poor soils or moderate slopes — could be considered candidates for biomass production. This will be especially true if there are even minor improvements in crop productivity through advances in genetic engineering or design of farm machinery, or if the value of biomass increases.[67]

Biomass production thus could lead to more multiple-use conflicts over currently forested land by adding another use to the land.[66,68] Farming trees that are genetically engineered for rapid growth, a goal of efficient biomass production, could increase the consumptive demand for land that is currently old growth forest habitat. Such uses of the land would reduce its recreational value to outdoor enthusiasts and reduce its value as natural habitat. It does not seem likely that genetically engineered trees, which could in essence replace natural forests, can be harvested without reducing and destroying the area as wildlife habitat, and as a traditional long-cycle timber producer. Old growth forest is required for the survival of many animal species, for example, the spotted owl and the red-cockaded woodpecker.[65,68] However, there is a possibility that biomass plantations may actually serve as a substitute for old-growth fiber, thus preserving this natural resource.

Intense management for biomass production will also aim to control damage to trees, some of which will be caused by wildlife such as deer and rabbits. Young plantations are especially vulnerable to damage under normal use by wildlife.[65]

c. ECOLOGICAL EFFECTS OF BIOMASS FARMING ON RANGELANDS AND DESERT AREAS

There are 330 million ha of rangeland in the U.S.,[69] of which 54% is federally owned.[65] Rangeland, 99% of which is in the West, consists mainly of grasses, with a high frequency of herbs and shrubs.[65] Grasslands, in areas characterized by low rainfall, periodic drought, and recurrent fire, once dominated the center of the North American continent.[70] Almost the entire extent of eastern prairies have been converted to cropland. Farther west, agricultural use has varied with the availability of moisture and the quality of the soil. Today, rangelands are typically associated with cattle-raising.

Because of overgrazing on both private and public lands, most rangelands are considered to be in poor condition.[65] Nevertheless, because rangelands are less intensively managed than other kinds of ecosystems, they do provide some productive habitat for wildlife. The Blue Mountains of Oregon and Washington alone support 378 species of vertebrates, and typical mammal and game bird species found on rangelands include pronghorn, elk, deer, badger, partridge, grouse and quail.[65] Expansion of intensively cultivated land into what is currently rangeland will reduce the number and diversity of naturally occurring species.

Winter conditions are often a pivotal element in supporting viable wildlife populations. Intensive uses of land for biomass production can be expected to reduce winter habitat,[67] although biomass could be grown specifically to diversify the environment and provide better winter habitat. A few other approaches, such as spring harvesting of herbaceous biomass from rangelands, might permit regeneration in time to provide adequate winter cover. On the other hand, the amount of biomass harvested in the spring would be less than if it were harvested in the fall, due to natural decay and winter grazing. Combining land uses for biomass production and winter ranging is likely to be an uncomfortable compromise. However, a critical analysis of available rangeland and its quality as winter habitat might reveal that some of these areas play only a marginal role in maintaining wildlife populations and would otherwise be suitable for biomass production.[65]

The impacts of biotechnology on rangelands could produce subtle, undesirable consequences. For instance, if genetic engineering developed effective biocides or other ways of eliminating mesquite *(Prosopis juliflora)*, considered a very damaging weed on rangeland, there would be complex consequences for native wildlife because the seed of the mesquite plant is an extremely important food for many animals.[65] On the other hand, if mesquite were to become a major biomass crop, given its regenerating capabilities and resistance to drought, it could result in changing the character of the land to the other extreme. This is a good example of the enormous range the prospects of biotechnology has in affecting land-use.

What about the direct impacts of raising tolerant crops on rangeland for biomass or harvesting the natural vegetation as a source of biomass? This would be feasible only if biomass products were more valuable than meat products. At the current state of development of biomass technology, this seems unlikely. There are, however, naturally occurring grasses in Europe and Africa that are very productive on very poor soils or in areas with low rainfall.[71] With the help of genetic engineering, some variant of these may find a U.S. market as a source of biomass in areas currently used as rangeland. While these grasses may indeed be more productive, the ecological consequences of previous introductions suggest this is likely to be highly destructive to native species. For example, Bock et al. demonstrated that many native animal populations declined in grasslands dominated by the introduced forage grasses *Eragrostis lehmanniana* and *E. curvula*.[71] In this case, the grasses were not even very attractive to cattle. Introduced grasses in California have replaced native grasses on an estimated 40 million ha of grassland. While this change allowed for greater cattle production on these grasslands than the native plants could have supported, it also represented massive decreases in native plants, many of which are now extremely rare.[72]

One aspect of rangelands that keeps them economically viable is that very little human or mechanical energy is used to sustain production. The native grasslands of the Great Plains maintained productivity under grazing for thousands of years.[70] It is likely that some exotic grasses can be introduced, or native grasses bred, to produce even greater yield on these lands, including yield for biomass. However, substantial increases in productivity for biomass will require more intensive management. It is important to note that, when irrigated, most dry areas in the U.S. can produce crops that are, at least at present, far more valuable than biomass. Biomass production can be expected to invade dry areas only where high salinity has rendered the cropland nonarable. It is unlikely that, on land which gets less than 80 mm. of rainfall a year, the total productivity could be raised to levels high enough to keep a biomass processing plant running.

Careful studies should be carried out before rangelands important to native species are converted to introduced grasses for biomass. While we could assert that we will learn from our mistakes, and would certainly not introduce a biomass crop that did not provide either biomass superior to native grasses or wildlife habitat, in fact, testing for these concerns and studying the long-term productivity of a grass are not trivial matters and would take decades to determine. An introduced perennial that is annually or frequently harvested might have any number of undesirable side-effects, including serious depletion of soil nutrients over time or enhancing fire damage.

The best applications of genetic engineering of herbaceous biomass are in rangelands that have been overgrazed to the point that they are not likely to recover. Modified species could encourage recovery of the land to make it productive again. Care will be needed, however, to ensure that traits effective during recovery are also beneficial after recovery.

d. ECOLOGICAL EFFECTS OF BIOMASS FARMING ON "MARGINAL LANDS"

Currently, wild animals are predominantly found on preserved lands. Only land that was difficult to till, for example being too wet, was spared the plow — thus surviving to form what are now our wildlands.[50] Although historically seen as useless waste areas, many of these places are important segments of complex food chains, sustaining species that spend most of their lives elsewhere. The term "marginal" really only applies to agricultural potential, since hunters, hikers, and a diversity of animal species consider them excellent habitat.

To reduce competition for relatively manageable land now used to grow food and fiber crops, it has been proposed that marginal lands be targeted for biomass production. For example, an estimated 3.4×10^7 ha not now in crop production have moderate or low potential for being used as cropland.[73] Deserts and desert margins, forested lands too difficult or remote for intensive agriculture, and cattail marshes are among the environments suggested for regular biomass harvesting.[41-43,74] These could be harvested as a source of plant material for biomass feedstock. Alternatively, since many biomass uses can be fulfilled with virtually any kind of plant material, very hardy crops could be grown on poor soils or degraded land. Perennial crops, such as short-lived shrubs and weedy trees, are often suggested for this.[74]

One obvious consequence that will result from more intense use of "marginal" lands is a decrease in the number of species that they support.[67] There are approximately 2100 wild vertebrate species occurring in North America, including 650 species of birds. In contrast, there are only a few dozen domestic livestock: cattle, sheep, goats, chickens, ducks, etc.[75] Biotech-enhanced biomass farming of lands that are currently not under agricultural production will permanently displace most wild users of these lands.

e. ECOLOGICAL EFFECTS OF BIOMASS FARMING ON WETLANDS

Wetlands are some of the most productive wildlife habitat, and they have been suggested as suitable for conversion to cattail energy factories.[43,44] Should genetically engineered wetland plants prove to be economical sources of biomass, a true ecological disaster could result because wetlands are integral components of surrounding ecosystems.

Major types of wetlands include prairie potholes, inland, delta, coastal marshes, flood plains, and swamps.[50] Wetlands contribute to local economies by supporting sport and commercial fisheries, game birds, especially ducks, and furbearers such as mink, beaver, and raccoons. They also maintain populations of songbirds, other vertebrates, invertebrates, and plants. Water, nutrients, and exposure to full sunlight combine to make wetlands extremely productive, and as such they are critical to the survival of a wide variety of species. For instance, in Texas and Oklahoma, seven times the density of birds are found in riparian (river edge) habitat as elsewhere.[76] If biotechnology increases the consumptive demand for fresh water, either as an application to biomass crops or for vat-culture technology, river flows will decrease, diminishing the quality of affected wetland habitat. Habitat will also be reduced if biotechnological advances produce moisture-tolerant crops that could then be grown close to streams and rivers, displacing naturally occurring plants. Wetlands must be given special priority for protection from changes that may follow application of biotechnological innovations to agriculture and silviculture.

2. Crop Residues as a Source for Biomass Production

Biomass can also come from residues left in the field after certain crops are harvested. It has been estimated that currently in the U.S. some 250 million metric dry tons are available for biomass from crop wastes, while still leaving an adequate amount of plant material to incorporate in the soil.[77] Although biomass from crop residues may yield less than what could be yielded from croplands dedicated for biomass production, it represents a resource which, if exploited correctly, can have potential benefit without leading to unfavorable consequences.

While collecting crop wastes can lessen subsequent productivity by reducing the quantity of fertile material incorporated back into the soil, most proposals for harvesting residues for biomass take that into consideration (e.g.,[77]). Many cropping systems, especially with mechanical harvesting, leave so much residue that it can actually be an impediment to the next crop and is burned, or the process of breaking it up consumes far more energy, and contributes fewer nutrients than if a cleaner harvest was made and appropriate fertilizer applied for the next crop.[77] In some areas where erosion is a problem, little residue can be safely removed. However, overall, there is still enough of a supply of crop residues produced by current agricultural processes that could be used for fuel and chemical production and be energetically advantageous and environmentally benign.[78] Whether or not crop residues could be wisely used as a biomass source in a self-sustaining manner will depend largely on political will.

Basing a biomass source on crop wastes means that it is likely to vary unpredictably. Market forces will dictate what crops are grown, which could in turn potentially lead to dramatic changes in feedstock availability if farmers switch to crops or harvesting processes which leave very different volumes of residue. Consequently, although a biomass industry based on crop waste could have some advantages, it is not likely to be very stable.

a. ECOLOGICAL EFFECTS OF USING CROP RESIDUES

Biomass could begin with any biological material, but usually it is plant material, since, of the metabolic processes in living systems, plants use the smallest molecules as feedstocks and capture the sun's energy with the least conversion steps and a minimum of energy loss. Plant material for biomass will have to be grown somewhere, so land, fertilizer, and human and mechanical energy for cultivation and harvest will be required. Use of agricultural residues or other wastes as feedstocks reduces these costs. This can be ecologically desirable if, overall, resources are used at a sustainable rate. In any case, residues have a very limited ability to meet production demands.

In addition to human use of agricultural land, it must be recognized that wildlife also exploit crop residues. For example, the bulk of the U.S. sandhill crane population, some 500,000 in number, survive on waste corn for six weeks every year while preparing themselves for northern migration; the grain provides 90% of their caloric requirements.[79] Although crop residues are critical to sandhill cranes, the birds consume only about 10 to 20% of the total residue.[79] Other species, from sparrows to deer, likewise rely on crop residues. In general, however, if practiced in a judicious, sustainable manner, there should be no conflict between humans and wildlife in sharing this resource.

B. Production of Biomass in Aquatic Systems

Biomass can also be produced in aquatic systems. Indeed, total production is often higher in aquatic ecosystems than on land because, among other things, the availability of water is not a limiting factor.[30] Although most research has focused on microalgae,[20,39] naturally growing populations of marine algae could be harvested for biomass, or the plants could be cultivated in coastal impoundments.[80]

Microalgae are microscopic photosynthetic organisms. Golden algae have attracted particular interest because they store energy primarily as lipids, which can be extracted and converted to fuel and chemical products.[20,39] Oil can comprise up to 65% of their body weight.[39] Microalgae can be cultivated in shallow ponds using saline groundwater or wastewater.[20,39,81] Most research is being done in deserts, where sunlight and saline groundwater are abundant and other resources for biomass production are lacking.[81]

Algal species that produce large amounts of oil tend to have slow growth rates. Research is currently underway to determine if DNA from organisms with high growth rates could be transferred to organisms with high lipid yields.[39] Thus, biotechnology could lead to advancements in production and processing, improving the cost effectiveness of algae as a biomass source.

1. Ecological Effects of Cultivating and Harvesting Aquatic Plants for Biomass

Large-scale harvesting of aquatic plants for biomass feedstock could potentially have negative consequences, especially if cultivated in coastal environments. If plants are grown in freshwater ponds, the ecosystem may be altered by manipulating the influx of freshwater or by supporting increased numbers of plants. Recurrent harvest of plants will inevitably modify aquatic food chains, and raising plants will affect the quality of water released downstream.

Similarly, although algal beds and coastal zones are often seen as wasted ''marginal lands'', they are in fact critical to the survival of many organisms, including invertebrates, fish and birds. Harvesting naturally growing populations of marine algae for biomass or cultivating the plants in coastal impoundments could be environmentally destructive. The ecological consequences of harvesting marine algae for biomass could include radical drops in populations of organisms which feed either directly or indirectly on the algae of the coastal zones, many of which are economically important. And the creation of coastal impoundments would drastically alter and displace shoreline ecosystems.

C. Industrial Wastes as a Source of Biomass

Industrial wastes, such as residual wood from pulp mills, could be considered another source of feedstocks. Biotechnology will influence this industry by formulating specific enzymes to aid in processing wood waste, which is generated in large quantities by pulp mills.[82] While the volume of usable waste from this source is projected to be minimal, this alternative source of biomass would not add competing pressures to existing land uses. Recycling these wastes would be both a profitable and environmentally practical means of reducing the amount of waste that needs to be treated and discarded.

1. Environmental Implications of Using Industrial Wastes as a Biomass Supply

As with crop residues, industrial wastes represent an important source of biomass for fuel or chemical feedstocks, but its potential applications are limited. Because crop residues and industrial wastes combined could supply only a small fraction of the potential demand for ethanol, these alternate biomass sources would not be able to relieve the potential long-term pressures on forests and rangelands that will likely ensue as a result of decreasing reliance on petrochemicals and fossil fuels.

Biomass produced using semipurified industrial or municipal wastes will probably leave sludge and heavy metal wastes. None of these products from biomass processing are worse than what is in the present waste stream, but increased volume may intensify environmental problems.

D. Biomass as a Feedstock in Production Processes Using Vat-Culture Technology

Currently, the most common chemical manufacturing applications for biotechnology entail modifying bacteria or single-celled fungi (yeast) by inserting a particular gene or genes. Cultured plant or animal cells can also be used.[15,83] Using these bioengineered organisms, vat-culture techniques can be applied, taking advantage of the well-established fermentation technology used to produce beer, yogurt, and cheese. Industries reliant on such compounds as alcohols, organic acids, and small proteins do not currently but probably will eventually use biotechnologically enhanced vat-culture methods of production.

Modified cells can be used in vat-culture methods either to produce the desired product directly from simple molecules, for example, ethanol from CO_2 and water, or they could be used to catalyze reactions in partly degraded organic matter (biomass) to then produce the desired product, for example, fermenting sugars into alcohol. Likewise, it has been projected that bioengineered catalysts or organisms will be used to produce molecules ranging from amino acids to flavors.[7,15,17,84,85]

In the most efficient vat-culture production methods, the desired compound is excreted by the cells. This allows removal of the product from the living cells and sustained production by the same cells. Thus, engineering microorganisms to produce and excrete molecules in vat culture is a very important direction for research. Vat culture is especially practical for the synthesis of small molecules with complex synthetic pathways.

For molecules too large for the cell to excrete, vat-culture technology can be employed by producing populations of microorganisms or cultured cells which are disrupted to extract the product. The cellular residue could be used as the substrate for growing more cells for continued production. This method is suitable to produce many nonsecreted proteins as well as such metabolic products as glycerol, storage polymers, and long-chained fatty acids.[9,15,86]

Development of enzymes that speed the breakdown of inert plant structures is an important direction for the future of the vat-culture industry. The molecules that form wood (lignin, cellulose) are all potentially convertible into alcohol molecules. While many microorganisms can use cellulose or lignin as a carbon source, the conversion is generally very slow by industrial standards, so that there is much room for developing genetic techniques to improve the process.[24] Success in making available high quality energy and chemical products from wood and wood byproducts lie in making wood a practical source of material for ethanol production using vat-culture technology.[87,88] It is possible that plantations of fast-growing poplar trees, bioengineered to be herbicide and pest resistant,[38,89] will eventually be used as feedstock to produce ethanol for a large fleet of transportation vehicles.

1. Ecological Impacts of Vat-Culture Technology

Vat-culture production is efficient, it physically contains recombinant organisms, and allows strict regulation of the inflows and outflows. However, this does not guarantee that it is environmentally safe. The feedstock that goes into the vat must be produced somewhere, with complex impacts on other land uses, and the effluents may harm or modify natural communities as well. However, experience with other industrial products which use vat-culture techniques suggest environmental impact can be made neutral or favorable.

Every technology produces some byproducts not consumed in the production. Byproducts of biomass production for ethanol include waste water, CO_2, lignin, hemicelluloses and small amounts of organic molecules such as turpentine and acetic acid, depending on the process used.[39] Microbial processes release waste waters containing varying amounts of the feedstock, depending on the process. Where field or forest wastes are used, biomass production will leave a variety of nonfermentable organic wastes. At present, the faster chemical pretreatment systems for wood processing (for pulp and paper) yield byproducts such as sulfur compounds, which may interfere with using such wastes as a feedstock.[36]

a. WASTE BYPRODUCTS ASSOCIATED WITH BIOMASS CONVERSION PROCESSES

Biomass-to-fuel conversion processes require large quantities of water. This means that should industrialization increase to keep up with demands for biomass fuels, water will be drawn from lakes and streams into the plants and the outflows will need to be treated to protect water quality downstream. Again, these problems are not unsolvable, but they are sources of concern to environmentalists.[11]

Moreover, chemical wastes are produced by existing methods of energy production. One clear possibility of biotechnology is to develop methods of handling these byproducts that are less toxic. As an example of the opportunities, consider the case of pulp mills, where the waste stream represents a potential source of raw material for fermentation of ethanol. Currently, the waste is too contaminated to be reused because of the chemical processing it undergoes to remove lignin, a step that is necessary to produce most papers. Biological methods of separating the lignin and cellulose are being sought to reduce contamination and improve the quality of the waste streams.[39] One promising option now in the experimental stage is to use organic residues from the waste stream as feedstocks to produce other compounds.[21,26,90,91]

There is also the possibility of novel problems. New biomass processes may generate toxic waste products different from those with which regulators are familiar, especially as a result of novel mixes of discarded wastes. Furthermore, biomass production augmented by biotechnology has the potential to amplify some obscure biological process, leading to, for example, the proliferation of a minor organism with unexpected consequences. The release of nutritious organic molecules, benign in themselves, have caused dramatic blooms of algae in nutrient-poor waters, consequently causing pollution.[92] Other effects might include displacement of established organisms through competition or release of toxins from the decomposition of organisms used in industrial processes.

A suite of specialized microorganisms will soon be available to detoxify industrial wastes and to substitute for normal chemical processes that pollute heavily. Some of these bacteria clean effluent waters by using the materials suspended in the water as a medium for growth and reproduction. This raises the question of how to dispose of the microorganisms. It seems probable that byproducts will be rendered nontoxic or even useful, possibly as a source of biomass, but we caution that this will not happen spontaneously and will require sustained research and development efforts.

One waste problem that will be peculiar to future applications of biotechnology involves the need to contain genetically engineered organisms with unusual features. In order to prevent microorganisms from spreading into unintended locations, it will be necessary to contain industrial organisms. Fungi bearing extremely efficient cellulases or highly productive algae may become pests in natural habitats if disposed of outside the industrial complexes. Because perfect physical containment is impossible, it may be prudent to engineer such organisms so that they perish once outside the vat environment. Applying this as an extra measure of protection (e.g., adding "suicide" genes[61] or chemical dependency), may slow development of the industry somewhat, but it would be highly beneficial for environmental safety, public acceptance, and reducing liability. While in most cases, acceptable containment will probably be possible through normal waste treatment, it would only take one exception to cause major damage to an ecosystem and loss of public confidence. As said above, biological containment methods should not become a substitute for thorough ecological analyses.

IV. ETHANOL MARKET PROJECTIONS AND INFLUENCE ON LAND USE

To be economically practical, biomass production requires easy access to the processing plant.[38,93] With large transportation costs, the technology becomes unprofitable. Only where a processing plant can be located within a reasonable distance of source material, whether it is crop residues with occasional forest products, or sufficient forest to maintain the manufacturing plant, will biomass production be economically feasible.

Productivity and harvesting costs are the most important considerations in determining overall costs for biomass production.[38] Biomass technology will be difficult to develop in geographic areas of very low plant productivity, so holding down the costs of transporting harvested biomasss to the processing plant will be all that more important. For example, harvesting in nonirrigated deserts will not produce enough biomass to keep processing plants going.

The U.S. currently uses 4.2×10^{11} l of gasoline per year[94] — an amount equivalent to 5.9×10^{11} l of ethanol in terms of energy. When considering diesel fuels used in trucks, jet fuels used in airplanes, and residual oil used in ships, the total transportation energy requirements are raised 40%[95] to a total demand of 8.3×10^{11} l of ethanol-equivalent per year. Production yield of plant species proposed as sources of biomass range from about 5.6 dry metric tons/ha/yr for wheat, to 50 dry metric tons/ha/yr for sugarcane.[41,42,43] Differences in length of the growing seasons account for a major part of the range in yields.

Assuming that a moderately productive biomass plant has an average yield of about 10 dry metric tons/ha, and can be converted to ethanol with an efficiency of 50% on a dry weight basis,[39] it would take 1.3×10^8 ha of biomass to provide an amount of energy equivalent to the current annual U.S. consumption of transportation fuel.

If ethanol production were to become cheap enough, or if the price of transportation fuels were to rise high enough, most cropland, forest, and grassland would be candidates for conversion to biomass. If the U.S. were to undertake a massive conversion to ethanol as the choice of fuel, dramatic changes in land use could occur. Currently in the U.S., approximately 1.7×10^8 ha is classified as cropland[96] of which about 1.3×10^8 ha was actively farmed in 1988.[97] Switching from gasoline to alcohol would mean, under our assumptions, that there would be twice the amount of U.S. land in crop production than there is now (totaling food, fiber, and biofuels crops). Conversion of cropland to biomass would be especially likely for land that has been marginally profitable in producing food crops, or for land that is not currently in production (e.g., 0.4×10^8 ha of the 1.7×10^8 ha above).[97] Biotechnology could influence the biomass market by increasing productivity and reducing costs, making it feasible for less and less productive land to be put into production, creating more and more pressure for conversions.

If biomass could be harvested from the 2.2×10^8 ha of privately held rangeland and pastureland in the United States,[96] 60% of these lands would be needed to meet transportation demands — again assuming a yield of 10 dry metric tons/ha/yr. Basing these rangeland estimates on a yield of 10 dry metric tons/ha/yr may be optimistic, so an even greater amount of those lands would be required to meet transportation demands for biomass fuel.

V. CONCLUSION

Technology has given humans so much power to develop economically that we have unintentionally become stewards of the earth, with the ability to contaminate our own environment and to destroy most of nonhuman life. Biotechnology applied to biomass and chemicals has great potential to solve some of the environmental problems that plague us today should other means fail, but it also carries with it the risk of causing new problems and exacerbating pressures on our global ecosystem.

Biomass may never become a dominant source of energy or chemicals, and so it is difficult to predict the land pressures that would result. Nevertheless, it is important that we — the ecologists, biotechnologists, and policymakers — identify the potential ecological side effects and unintended consequences of biomass technology before they occur, especially when a strong biomass industry could lead to the alteration of hundreds of millions of hectares in the U.S. alone.

Whether native vegetation is harvested for biomass production, or forest and rangeland are converted to biomass croplands, large changes in land use will mean a loss of habitat for wildlife. In developing countries, conflicts over land use are already intense where cash crops for export are grown at the expense of food for residents.[98] If biomass products become valuable, such a conflict could arise and become a serious problem in the U.S. as well. This is especially likely for land held under corporate and multinational corporate ownership, since, having the resources to do so, they may choose to get in the total business of biomass farming and production for fuel and feedstocks rather than simply growing food crops.

Our hope is that by calling attention to the potential ecological effects of biomass technology, biotechnologists would realize the benefits of and direct their research toward "designing" products that could actually improve wildlife habitat. Without recognition of and a change in emphasis on environmental quality, genetic engineering for the production of energy and raw materials will likely take place independent of providing environmental protection. It would be much wiser and cheaper in the long-run to better integrate environmental concerns into energy biotechnology planning from the beginning. Because the technology is new, the opportunity exists to channel biomass engineering into environmentally sound directions, integrating environmental safeguards into the product design process.

Perhaps genetic engineers can work with ecologists in developing ecosystems for biomass production that support vertical, spatial, and age diversity, while still providing good economic return. This might be done by genetically tailoring a variety of plants/trees to work well together in an ecosystem, whereby, for instance, the biomass material returned the right kinds of nutrients to the soil for long-term productivity. Again, we emphasize that these aims need not be at the expense of good production.[99,100]

What overall vision can we put forward that will guide us in the wise development of fuels and chemicals from biomass? Consider a world where, from the university to the process laboratory to the corporate board room, it is second-nature to design new products that are highly profitable while sustaining basic environmental resources and maintaining wildness and wildlife diversity. Wastes from other industries would be used to produce energy and industrial feedstocks, leaving the environment cleaner at the end of the process. Imagine a regulatory system, consistent across countries, where those who adhere to these standards are protected from unfair competition from those who do not. A naive vision? Perhaps, but if we do not strive for such a world, we will end up not only having robbed future generations of their natural heritage, but we will leave behind a world in which much of their productivity is spent fixing the environmental problems from our generation.

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