In Williams, C.G., *Landscapes, Genomics and Transgenic Forests,*
Kluwer, Dordrecht (in press).

CHAPTER 2

FORESTERS AND DNA

Jesse H. Ausubel
The Rockefeller University, New York NY, USA ausubel@rockefeller.edu

Paul E. Waggoner
Connecticut Agricultural Experiment Station, New Haven CT, USA

Iddo K. Wernick
The Rockefeller University, New York NY, USA

Abstract. Would editing a few bytes of the genetic message for a tree to fit human desires do harm or good? To meet demands of larger populations and changing diets, farmers have used a series of innovations to lift yields and thus reduce the area of land needed to support a person. Since 1950 rising yields have stabilized land for agriculture and now promise a Great Restoration of nature on land spared. Foresters have also lifted yields and could lift them much higher, thus sparing natural forests while meeting demand for wood products, whose growth is anyway slowing. While weak demand, numerous worries, and vague promises will slow penetration of genetically modified trees, any technology that improves spatial efficiency has appeal, and editing DNA could lift yields. Both farmers and foresters must work precisely, using fewer hectares and more bits. Fortunately, foresters have several decades in which to test and monitor their practices before genetically modified trees will diffuse widely.

1. INTRODUCTION

The decoding of DNA messages produces magnificent structures, perhaps none more magnificent than a tree. Our question is, would editing a few bytes of the message for a tree to fit human desires do harm or good?

Forests do an admirable job of collecting solar energy and storing it in stable chemical form. The problem is spatial. The collected energy of trees is spatially dilute and in forms awkward to handle. Harvesting requires lots of manpower and sophisticated machinery. Further, harvesting is only the beginning. The bulky, round, solid biomass harvested from trees is unsuitable for convenient transport techniques developed for oil and gas, or for molding techniques matching plastics.

Consequently, Americans and most of the rest of the world have been abandoning wood in favor of the so-called fossil fuels and the plastics they become. Since 1800, wood and hay have plunged from a 90 percent market share of primary energy to less than 10 percent for the world and less than 2 percent for the United States in the year 2000. During the twentieth century, plastics replaced much timber, too (Figure 1). Even paper now struggles to hold its share of a dollar spent, as ubiquitous flat-screen monitors and e-books threaten to replace it. Paradoxically, in large tropical regions, people hack down forests resplendent with life for little gain of useful material or income.

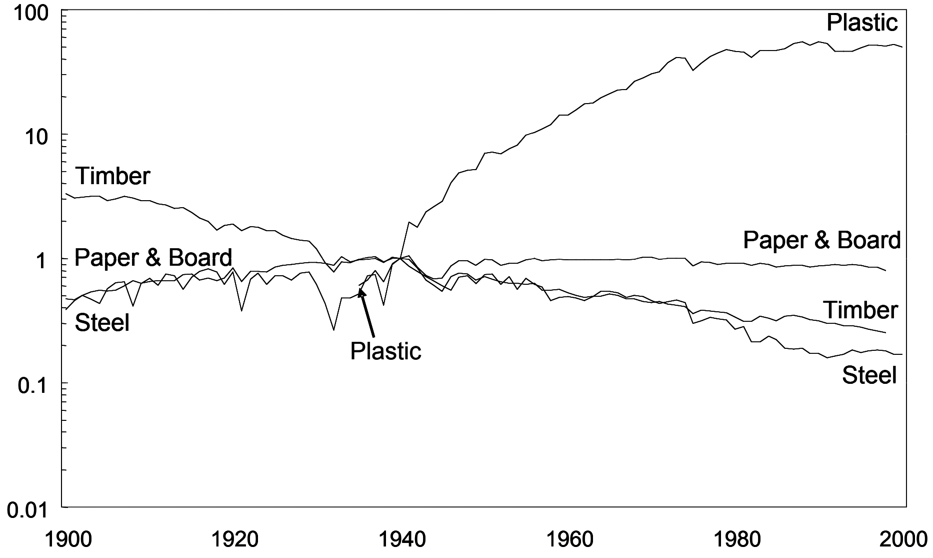

Figure 1. *U.S. intensity of materials use, 1900-2000. The y-axis shows kilograms per constant dollar indexed to 1940 on a semi-log scale. For example, consumption data for timber are divided by GDP in constant 1996 dollars and indexed to their value for 1940. Data sources: Ince, 2000; U.S. Geological Survey, 2004; Chemical & Engineering News, 2001; Wernick and Ausubel, 1995.*

The idea of a tree remains supremely elegant: living hardware automatically produced and maintained by coding of genetic messages whose raw materials are collected mainly from the atmosphere (Marchetti, 1979a). Could science help forestry survive while at the same time sparing the forests? Our answer is yes, through improving spatial efficiency, a path that leads foresters ultimately to DNA.

2. THE FARMER'S PLOT

Let us begin to grasp spatial efficiency by considering first the much more numerous cousins of foresters, farmers, who have edited DNA messages longer. Analysis of farming shows a coherent pattern of evolution from Neolithic times up to our new millennium (Marchetti, 1979b). Farmers have exploited technical advances fundamentally for intensification, to increase the specific productivity of land, to earn more from a plot. Yields per hectare measure the productivity of land and the efficiency of land use. Low yields squander land, and high yields spare land.

Beginning as hunter-gatherers, humans differed little from other animals. We met the pressure to grow by extending our geographical habitat. But we also extended our range of digestible foods, achieving great breakthroughs with energy. Plants defend themselves against predators with a panoply of armor and weapons. The most important are chemical and tend to make the plant indigestible and occasionally poisonous. Animals developed other defenses. Human genius was to apply thermal treatment to upset or destroy the delicate organic chemistry of defense. Boiling softens flinty rice and maize, and ovens convert pasty wheat into bread. Seven minutes of boiling soybeans denatures the trypsin inhibitor that would otherwise render tofu useless to us. Fire revolutionized food, permitting digestion of much plant material and seeds in particular, and in most cases improving taste as well. Fire extracted more nourishment from the same acres as well as nourishment from acreage formerly yielding none.

Farming in turn amplifies the production of biological material that we can assimilate directly or by thermal treatment. Humans ally with certain plants by collaborating in their reproductive cycle and by fighting their natural enemies. We put ourselves first among selective forces, picking the plants most profitable from our point of view.

What then has driven the laborious development of agriculture? After filling available geographical niches, the only way to expand is intensification. Like fire, agriculture essentially reduces the amount of land needed to support a person. The fruits of agriculture consequently support the human drives to multiply and to increase consumption.

Draft animals were the first big advance. Draft animals did not reduce human toil. Peasants with animals sweat as much as those without, as Paul Bunyan and his Blue Ox, Babe, would attest. Nor did oxen, buffalo, and horses drastically lift the productivity per worker, though an Iowan with a team could till far more than an Incan with a spade. Draft animals did increase the specific productivity of the land. Ruminants are the most successful symbiotic draft animals, consuming little human food but digesting roughage and poor pasture, as they extract energy from cellulose and manage nitrogen in the rumen's flora. Still, draft animals take land. In some farming systems, oxen, buffalo, and horses eat the yield of one-quarter of the land.

After World War II, the automobile industry produced solid, cheap, dependable tractors that pulled as powerfully as ten teams of oxen. Tractors proportionately increased the productivity of labor, but without substantially intensifying production. By draining land, they extended farming, and by freeing land that had grown timothy and oats for draft animals, they shrank it. Tractors released workers from the farms, but alone they grew little more corn per hectare. The story of forest machinery is the same.

Chinese agriculture represents an important counterpoint, an improvement of yield per hectare that saves land rather than labor. By 1900, without machines but using a thousand bioinformatic tricks, Chinese farmers reduced to 100 square meters the amount of land needed to support a person. Compare this space, about equal to a one-bedroom American apartment, to a few square kilometers for a hunter-gatherer. The difference is a factor of 10^4, or 10,000 times in intensification.

The ecological systems farmers create, although often visually appealing, bear no resemblance to any natural ecosystem, if only because of great structural simplification. Equilibrium and resilience tend to be lost, and the spatially efficient system becomes unstable and challenging to manage. No farm reproduces itself year after year without a farmer. The wits and toil of almost half the Chinese population are still employed to keep their farms going.

Because few societies could approach the summit the Chinese reached by labor, for most of the world farm evolution could continue only with a qualitative breakthrough. It came, like cooking, with the introduction of external energy, in this case fossil fuels. Starting around 1900, we not only tamed machines for the same purposes as draft animals but also started to synthesize as well as mine chemicals that hugely increased yields.

The effect of chemicals fits the master trend of intensification perfectly. Fertilizers, most obviously, are intensifiers. In the form of dead fish and animal droppings such as guano and manure, they have always been used to increase yield per plot. The external energy of fossil fuels permitted massive, economical, and convenient nitrogen synthesis beginning about 1950. Geneticists called crop breeders also began to deliver plants that yielded more product per hectare.

The diffusion of the innovations made average U.S. grain yields, rising very slowly for two centuries until about 1940, leap fourfold by 2000. In fact, on all continents during the past half century, ratios of crops to land for the world's major grains—corn, rice, soybean, and wheat—have soared (Waggoner, 1996). The breakthroughs in harnessing external energy and editing DNA allowed farmers to spare land, as production grew by intensification much faster than population. By tripling yield since the mid-1960s, India's wheat farmers, for example, have spared about 50 million hectares, about 80 percent of the present area of India's woodlands (Figure 2).

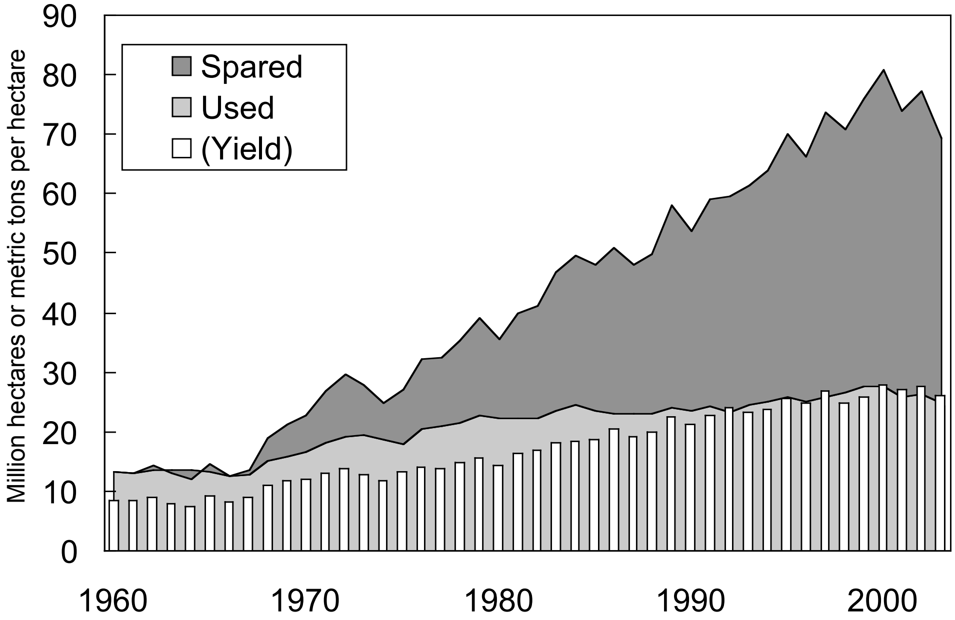

Figure 2. *Land spared by Indian farmers by raising wheat yields. The white bars show annual yields in metric tons per hectare. The light gray area shows land actually farmed in million hectares, while the dark gray area shows the additional hectares that would have been needed to produce actual output had yields remained at the level of the early 1960s. Source: Waggoner, 1996 (updated).*

3. THE GREAT REVERSAL

For centuries, globally, cropped land expanded and cropland per person rose, as more people sought more protein and calories. But about 1950, by rapidly lifting the specific productivity of land, the world's farmers stopped plowing up nature, and the worldwide area of cropland per person began dropping steeply. While diet improved, the land used to feed a person halved from almost half a hectare in mid-century to about one-quarter in 2000, signalling a great reversal of human extension into nature (Ausubel, 2001). Per hectare, the global Food Index of the Food and Agriculture Organization (FAO) of the UN, which reflects both quantity and quality of food, rose 2.3 percent annually between 1960 and 2000 (Food and Agriculture Organization, various years). In the United States in 1900, the protein or calories raised on one Iowa hectare fed four people for the year. By the year 2000, a hectare on the Iowa farm of master grower Francis Childs could feed 80 people for the year, comparable to the most intensive Chinese agriculture (National Corn Growers Association). The Chinese, of course, kept lifting the comparison as they lifted cereal yields 3.3 percent per year between 1972 and 1995. A cluster of innovations including not only tractors, chemicals, and seeds but also irrigation, joined through timely information flows and better organized markets, raised the yields to feed billions more without clearing new fields.

High-yield agriculture need not tarnish the land. The key is precision agriculture. This approach to farming relies on technology and information to help the grower use precise amounts of inputs—seeds, fertilizers, pesticides, and water—exactly where they are needed. We have mentioned two revolutions in agriculture in the twentieth century. First, the tractors of mechanical engineers saved not only the oats that horses ate but also labor. Then chemical engineers and plant breeders made more productive plants. The present agricultural revolution comes from information engineers, some of whose code is DNA. What do the past and future agricultural revolutions mean for land?

The agricultural production frontier remains open. If during the next 60 to 70 years, the world farmer reaches the average yield of today's U.S. corn grower, the 10 billion people then likely to live on Earth will need only half of today's cropland. This will happen if farmers maintain on average the yearly 2 percent worldwide growth per hectare of the FAO Food Index, slightly less than the record achieved since 1960. Even if the rate slows to half, an area the size of India, more than 300 million hectares, could revert from agriculture to woodland or other uses (Waggoner and Ausubel, 2001).

Meanwhile, the unnecessarily high cost in energy of modern agriculture should be reduced. The cost can be split between machines and chemicals. In energy terms, they represent about equal inputs. Most of the work of the machines goes into tillage, whose main objective is to kill weeds. Low-tillage techniques are, however, improving and spreading. Low-tillage farming uses herbicides to control weeds after seeds are planted by injection in the soil.

Herbicides and pesticides that now operate on the principle of carpet bombing are moving progressively to the hormonal and genetic level and require less and less energy as the amounts of product needed are reduced. The big slice of energy taken for fertilizers, nitrogen in particular, could be produced by grains capable directly, or through symbiosis with bacteria, of fixing nitrogen from the atmosphere. Improved tractors, minimum tillage, targeted herbicides and pesticides, and an extended capacity for nitrogen fixation might reduce farmers' energy consumption by an order of magnitude.

Lifting yields while minimizing environmental fallout, farmers can offer hundreds of millions of hectares for a Great Restoration of nature. The strategy is precision agriculture. Marchetti (1979b) describes it as more bits and fewer kilowatts.

4. LAND NEEDED FOR WOOD

Farmers may no longer pose much threat to nature. What about lumberjacks? As for food, the area of land needed for wood begins with a multiple of population and income, and then continues with the ratio of the wood products to the economy measured as gross domestic product (GDP). Let us focus on industrial wood—cut for lumber, plywood and veneer, pulp for paper, and fuel—and on the United States, always a pioneer and exemplar in resource use, good and bad.

Between 1900 and 2000, the national use of timber products grew about 70 percent. Meanwhile, at the end of the century, Americans numbered more than three and a half times as many as at the beginning, and an American's average share of GDP had grown nearly fivefold. Had timber consumption risen in constant proportion to population and income, Americans would have consumed 16 times as much timber in the 1990s as in 1900, not a mere 70 percent more (Wernick et al., 1998).

Industrial ecologists call a ratio of material to GDP its intensity of use. Because the annual percentage change of GDP is the sum of the changes in population and an individual's share of GDP, a constant intensity of use means consumption is rising in step with the combined rise of population and personal GDP or income. A constant intensity of timber use would mean timber played the same role in the economy in 2000 as in 1990 or 1900.

Practically, what lowered the intensity of timber use, or the ratio of timber products to GDP? For lumber, its replacement during the century by steel and concrete in applications from furniture and barrels to railroad ties and lath lowered the intensity of use. Living in the stock of existing houses and prolonging the life of timber products by protecting them from decay and fire lowered it. For pulp, more widespread literacy and the shift to a service economy raised the intensity of use in the early twentieth century, and then television and the Internet replaced newspapers, lowering the intensity of use.

Overall, after three centuries of cuts, history shows the extent of forests in the United States changed little in the twentieth century **(**Figure 3**)**.

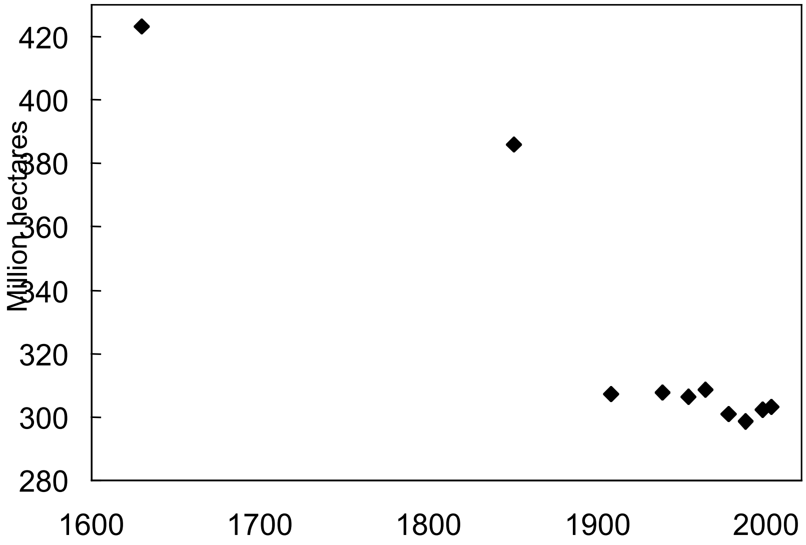

Figure 3. *U.S. forest land area, 1630-2002. Data sources: Fedkiw, 1989; USDA Forest Service, 1997 and 2002.*

Large areas formerly cleared have regenerated in New England and the upper Great Lakes states. Overall, in the United States, timberland plus forest area reserved for wilderness increased 9 percent during the period from 1992 to 2002, about 1 percent per year. Furthermore, reversing hundreds of years of depletion, the volume of wood on American timberland has risen about 40 percent since 1952 **(**Figure 4). Analysts have observed such a transition from deforestation to reforestation and afforestation in scores of countries (Mather et al., 1999; Myneni et al., 2001; UN ECE/FAO, 2000).

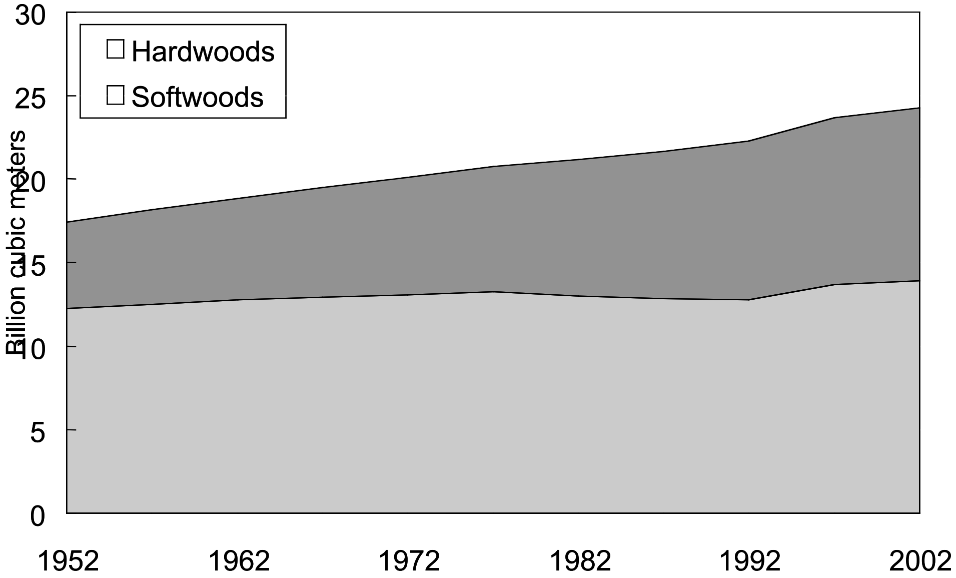

Figure 4. *U.S. forest volume, 1952-2002. Data sources: USDA Forest Service 1992, 1997, 2002*

Because the average contemporary American annually consumes only half the timber for all uses as a counterpart in 1900, U.S. forests expanded rather than shrank. Amidst a housing boom, demand for lumber has become sluggish, and world consumption of boards and plywood has actually declined in the last decade. Even the appetite for pulpwood that ends as sheets of paper has levelled.

Meanwhile, more efficient mills carve more value from the trees people cut (Figure 5). Because waste is costly, the best mills, which operate under tight environmental regulations and the gaze of demanding shareholders, already use everything but the whine of the saw as meatpackers once used everything but the squeal of the pig. In the United States, for example, leftovers from lumber mills account for more than a third of the wood chips that are turned into pulp and paper, and what is still left is burned for power. In 1970, American consumers recycled less than one-fifth of their paper, while today the world average is double that. Recycling closes leaks in the paper cycle.

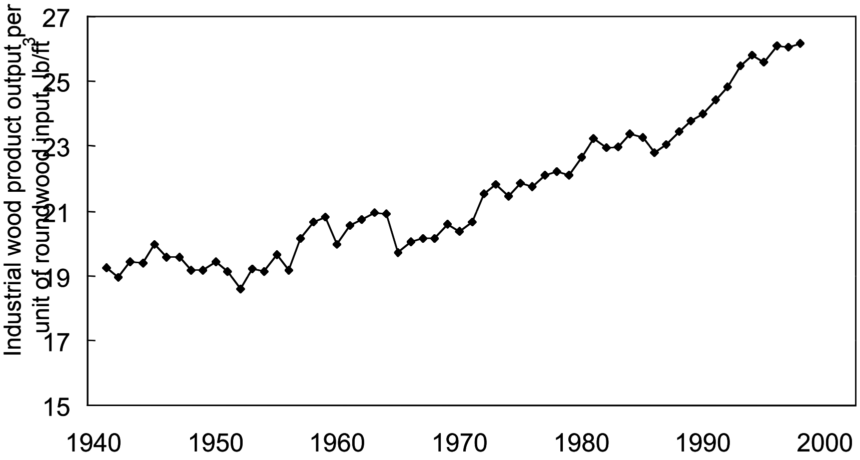

Figure 5. *Industrial wood productivity in the United States, 1941-1998. Date source: Ince, 2000.*

The wood products industry has learned to increase its revenue while moderating its consumption of trees. World demand for industrial wood, now about 1.5 billion cubic meters per year, has risen only 1 percent annually since 1960, while the world economy has multiplied at nearly four times that rate. If millers improve their efficiency, and if manufacturers deliver higher value through the better engineering of wood products while consumers recycle and replace more, demand for timber in 2050 could be only about 2 billion cubic meters per year and thus permit reduction in the area of forests cut for lumber and paper.

5. SKINHEAD EARTH OR GREAT RESTORATION?

The permit, as with farming, comes largely from lifting yield. The cubic meters of wood each hectare grows each year provide large leverage for change. Like fishers and hunters, foresters for centuries hunted and fished out local resources and then moved on, returning only if trees regenerated on their own. The effect was to shave Earth's forests from about 6 billion hectares 8,000 years ago to about 2.3 billion hectares of nonindustrial forests and 0.9 billion hectares of industrial forests now. Most of the world's forests still deliver wood the old-fashioned way, with an average annual yield of perhaps 2 cubic meters of wood per hectare.

Fortunately, industrial foresters are rising to the challenge of spatial efficiency. Forest yields have grown steadily during the past 50 years, as a series of innovations, mechanical, chemical, and informational, have diffused through the forestry sector (Figure 6). Yields have multiplied six times in pine plantations in the southern United States. Logically, the area of pine plantations has climbed steeply, in the South from about 800,000 hectares in 1950 to about 14 million in 2000.

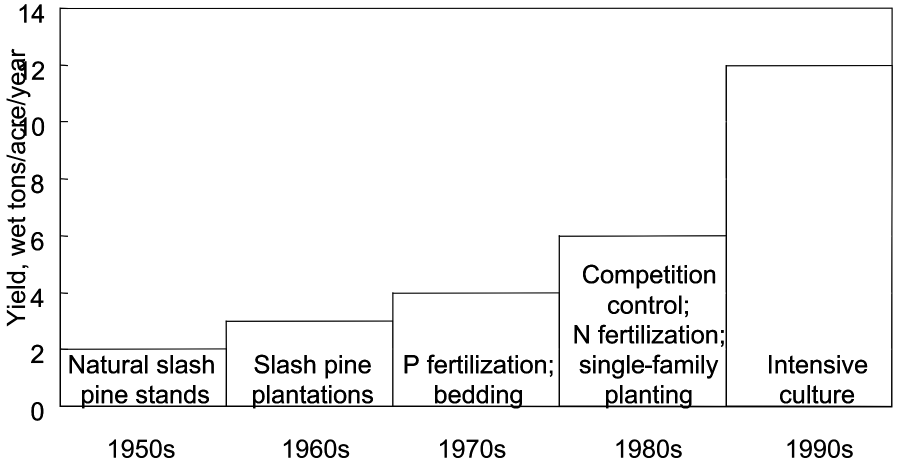

Figure 6. *Sources of rising yield in pine plantations in the southern United States. Source: Wann and Rakestraw, 1998.*

At likely planting rates, at least one billion cubic meters of wood—half the world's supply—could come from plantations by the year 2050 (Sedjo, 2001). Seminatural forests that regenerate naturally but are thinned for higher yield could supply most of the rest. Small-scale traditional "community forestry" could also deliver a small fraction of industrial wood. Such arrangements, in which forest dwellers, often indigenous peoples, earn revenue from commercial timber, can provide essential protection to woodlands and their inhabitants.

More than a fifth of the world's virgin wood is already produced at yields above 7 cubic meters per hectare. In Brazil, Chile, and New Zealand, plantations of selected species and varieties sustain yearly growth of more than 20 cubic meters per hectare. In Brazil hardwood eucalyptus good for some kinds of paper delivers more than 40 cubic meters per hectare, and the Aracruz Cellulose Company has recorded yields greater than 70 cubic meters per hectare per year. In the rainy Pacific Northwest and British Columbia, hybrid poplars deliver 50 cubic meters per hectare. The requisite informational innovations are increasingly biological.

If yield remains at the "natural" rate of 2 cubic meters per hectare, by 2050 lumberjacks will regularly saw nearly half the world's forests (Figure 7), a dismal vision of a chainsaw every other hectare, "Skinhead Earth" (Victor and Ausubel, 2001). The spatial efficiency of higher yields, however, will spare forests. Raising average yields 2 percent per year would lift growth over 5 cubic meters per hectare by 2050 and shrink production forests to just about 12 percent of all woodlands—a Great Restoration. Today's 2.4 billion hectares used for crops and industrial forests expand to 2.9 billion hectares on Skinhead Earth, while in the Great Restoration they contract to 1.5 billion.

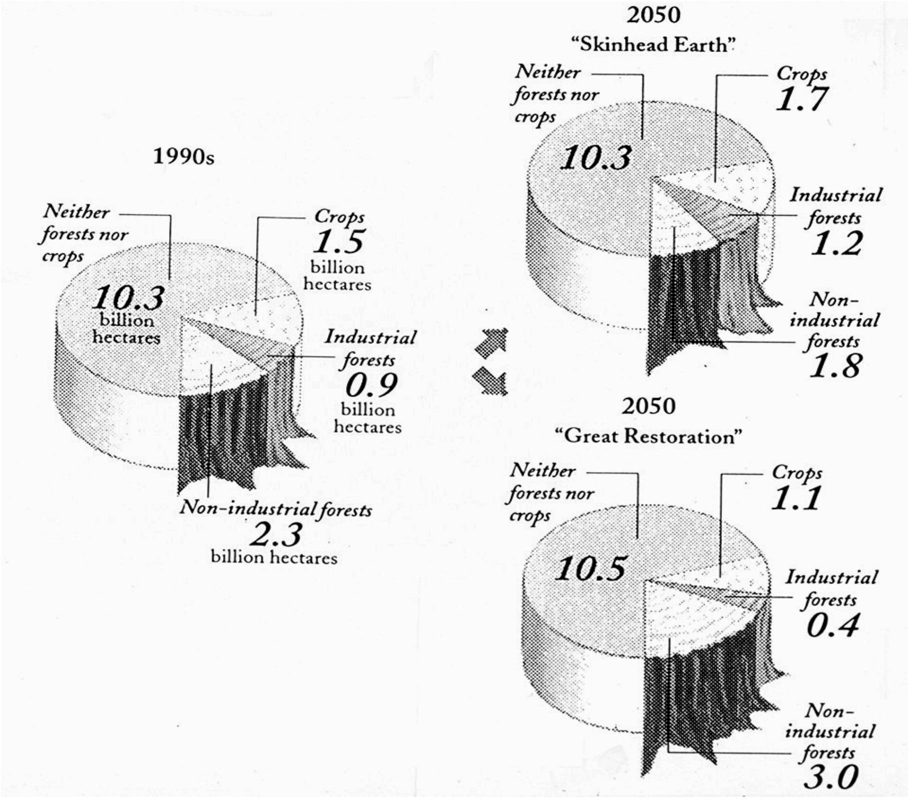

Figure 7. *Present and projected global land use and land cover. Source: Ausubel, 2002.*

6. DNA WORRIES

Facing paths toward Skinhead Earth or Great Restoration, we must now address the controversy at the root of forest genomics. Would editing a few bytes of the message for a tree in the same way the messages for food crops have already been edited do harm or good? We have clearly declared ourselves for lifting yields and intensification. As for means, anything that works with minimal fallout interests us. The foresters in Brazil and British Columbia, like Chinese rice farmers, have achieved high yields with a bunch of clever tricks, many cellular and genetic, but few would be labelled "genetic engineering" in the formal sense of gene-splicing. In fact, the breeding and management that transformed crop production in the twentieth century have scarcely been tapped in forestry and could lift it for several decades. Still, DNA is the sanctum sanctorum of biology, and now that humans have unlocked it, humans should consider the consequences. Evaluation of genetically modified trees requires examining the promises that would tempt people to plant genetically modified trees as well as the risks that should worry the planters. First, the worries.

6.1 Genetically modified plants encourage plantations

Because genetically modified trees are likely to be set in plantations, they raise the issue of unnatural forest plantations. Worriers should clarify whether they worry about plantations or genetically modified trees and not confuse the two issues. Some environmentalists worry that industrial plantations will deplete nutrients and water in the soil and produce a vulnerable monoculture of trees where a rich diversity of species should prevail. Would opponents rule out all genetically modified trees for fixing greenhouse gases or only plantations of single-species forests like eucalyptus, acacia, or pines? What if new genetically modified tree plantations are established on abandoned croplands, which are already abundant and accessible?

6.2 Genetically modified plants encourage concentration on a few species

Although foresters now use about a thousand tree varieties for industrial wood production, geneticists are likely to edit the DNA of only a few. Genomics might further concentrate forestry on a handful of species and thus increase vulnerability to catastrophic failure. In agriculture, nine plants and three animal species provide 70 percent of the world's food, and research has tended to concentrate on only those rather than diversify food sources.

6.3 Genetically modified plants violate nature

A purist might deplore any meddling or violation by humanity of nature's ancient genetic pool, especially in forests. With new mixtures of genes, genetically modified plants increase global biodiversity in a sense, as mutation does. Nevertheless, because humanity made genetically modified plants, some will worry philosophically that, whether genetically modified trees expand or shrink biodiversity, they violate nature. A proper philosopher would go on to examine and define the meanings of violate and natural. Baking bread is hardly natural, either. Bread does not grow on trees. At the same time, ethicists can easily imagine irresponsible or frivolous applications such as leaves that glow in the dark with a product endorsement.

6.4 Genetically modified plants endanger

Beyond *philosophical* worries lie tangible, *practical* dangers to worry planters and onlookers. For genetically modified *food crops,* health or dietary worries might be expected to head the list. Little if any evidence so far shows genetically modified foods cause damage to health. Admittedly, viewing genetically modified trees as a risk to health is a stretch, but research could bring relief to worried onlookers.

Economic and political worries will surely arise. Opponents of genetically modified crops assert the debate is in part about who controls the food chain from the seed to production and even distribution. Genetically modified trees are likely to elicit analogous worries about economic domination associated with highly capitalized, hierarchical enterprises that can afford to influence governments. Advocates for indigenous peoples, who have witnessed the harm caused by crude industrial logging of natural forests, warn that big corporations concentrated on global profit will dislocate forest dwellers and upset local economies with plantations.

Ecological worries certainly exist. Genetically modified transplants, seed, and especially pollen will inevitably escape. To survive, the escapee must be evolutionarily fit. The question that follows, and a hard one to answer, asks what practical danger an evolutionarily fit escapee poses. Although kudzu and multiflora rose are not genetically modified escapees, they give the perspective of historical experience to worries about practical dangers. A more speculative worry is that a transgene might accidentally switch on “sleeper” genes or silence currently active genes. Although pests might overcome genetically modified host resistance, the selection of successful pests is not peculiar to genetically modified pest control. Worries like escapees and resistant pests are less about the trees than about the forest, that is, that parts of the landscape in some way may become less appealing.

7. DNA PROMISES

What then are promises that might drive the planting of genetically modified trees?

7.1 Faster growth and land sparing

Faster growth drives the planting of genetically modified trees. For entrepreneurs faster growth appeals because it means profits sooner. For us, the appeal of faster growth is spatial efficiency. Low yields squander land, while high yields spare it. Appropriately, the foremost promise of genetically modified trees is for the landscape, to hasten the Great Restoration.

7.2 Improved product

Investors seeking more practical benefits than the Great Restoration of nature will care about improved product as well as faster delivery. Conceivably, modified genes could tune trees more closely to users’ needs, for example, for tree form or uniform wood quality, than simply selecting species or varieties. Tested over time, genetically modified trees may grow shapes with fewer branches and more trunks that can be formed into products.

Practical screening of genetically modified cells among millions of candidates demands a well-defined, easily assayed characteristic. In crops, abilities to emit a toxin that clears the bacterium in the culture medium or survive a herbicide in the medium have made ideal characteristics to speed screening. In trees, lignin content is well defined, and a clever assay for cells rich or poor in lignin may be designed. On the one hand, lignin makes lumber strong. Builders lay hardwood floors rich in lignin. On the other hand, paper mills prefer softwood pulp already low in lignin because it otherwise must be removed with costly, environmentally hazardous chemicals. Thus, the analogue in trees of the genetically modified, golden rice with richer vitamin A could be trees rich in lignin for lumber or poor for pulp.

7.3 Pest resistance

Because corn and cotton transformed to produce *Bacillus thuringiensis* have spread across millions of hectares and saved tons of insecticide, one looks for analogues of this success in forestry. Forests have pests, too. After World War II, some proposed spraying DDT from used bombers onto millions of acres of forest. Although trees’ long life cycle could give pests more chance to develop resistance to the toxins, transforming trees to produce pesticide and prevent defoliation holds promise.

7.4. Herbicide resistance

The relatively straightforward selection of transformed cells that survive the herbicide Roundup has made Roundup Ready crops a pre-eminent success in agronomy. Although herbicide resistance would not likely help to maintain a plantation, it might help establish it.

7.5. Growth in harsh environments

Editing DNA so that trees could reclaim land damaged by erosion or salt would be beneficial. Other analogues of crops transformed to grow in harsh environments could be imagined.

7.6 Carbon fixation

Transforming trees into faster producers of wood and fixers of greenhouse gas could benefit those who fight climate change.

7.7 New varieties quickly and cheaply

Producing a single new variety of a well-studied species such as the apple costs about half a million dollars and 15 to 20 years even with marker-assisted breeding and tissue culture. Although forest genomics may cost a lot at the outset as genomes are sequenced, subsequent innovation could be quick and thus cheap.

7.8 Wood at a competitive price

As the wood products industry struggles to compete, large parts of it will suffer unless the price of stumpage compares favorably with plastics and other alternatives. Jobs for foresters, millers, and carpenters may finally depend on keeping the commodity price low. The time when genetic engineering could be a top contributor to cost control seems distant, but the several ways genetic modification could eventually boost wood growth and quality finally might sum high.

8. HOW FAST MIGHT MODIFIED TREES PENETRATE THE FOREST?

Many worries about genetically modified trees may be ill defined, but the promises are, too. Until something more effective than a United Nations recommendation to fix carbon dioxide in forests, genetically modified trees are likely to remain scarce and little reason to worry. Still, how fast might genetically modified trees penetrate the forest?

The economy and effectiveness of pest control have propelled the rapid diffusion of genetically modified *crops* (Figure 8). As a reference for speed, we can compare the current national speed of adoption of genetically modified soy, corn, and cotton with the classic adoption of hybrid corn in Iowa, Kentucky, and Alabama. While hybrid corn took 6 to 10 years to diffuse within American states, the new crops are taking 10 to 20 years. Globally, genetically modified crops appear likely to diffuse over about 20 years. Recent decisions from Brazil and Paraguay to the European Union suggest the global pace will be maintained.

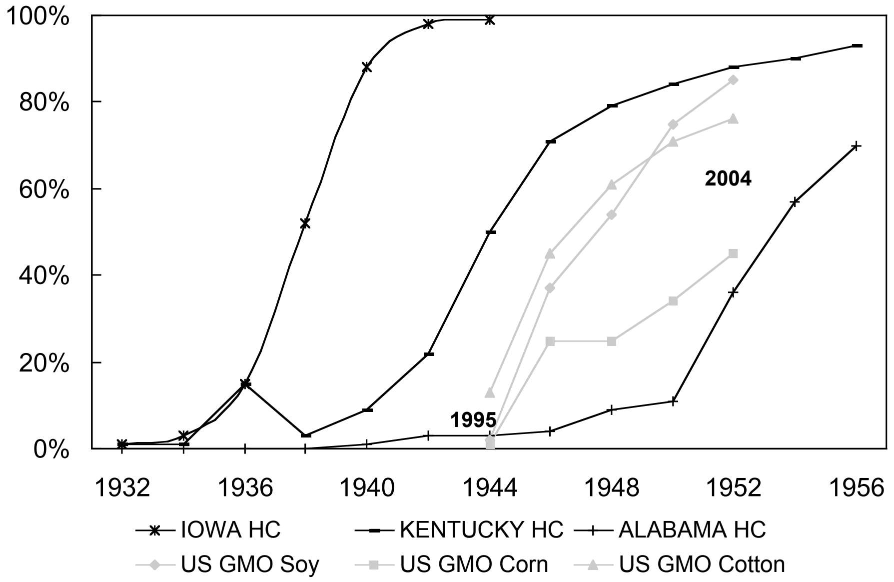

Figure 8. *Comparative diffusion of hybrid corn and genetically engineered crops. Adoption of hybrid corn is shown as a percent of the total corn crop for three U.S. states from 1932 to 1956; in gray is adoption as a percent of total crops of genetically engineered soy, corn, and cotton crops in the entire United States from 1995 to 2004. Sources: Griliches, 1988; International Service for the Acquisition of Agri-Biotech Applications, 2004.*

The slow life cycle of 25 to 100 years from planting to harvest will inevitably retard the diffusion of new kinds of trees. But adopting genetically modified trees as fast as genetically modified crops is most likely for plantations. Even in plantations where the adoption of modified trees is most likely, the cropping cycle of, say, 30 years for pine versus 1 year for corn must be remembered. Should modified trees achieve a cycle of, say, 15 years to harvest, it would speed planting on fresh land. Existing plantations would be little affected until the present growing stock could be economically replaced. If trees planted in 2010 or 2020 matured as fast as hemp, plantations would change much sooner.

Although forest owners might be propelled to plant genetically modified trees, how much land do they own? Owners in the U.S. forest industry, who are most likely to plant modified trees, own only about a tenth of the 300 million hectares of U.S. forest. Penetration of modified trees requires planting on land they already own or on abandoned land they may buy. As a guide to what might be planted, consider present planting rates. In 2000 the United States had about one-tenth of the world's 187 million hectares of tree plantations. In relative terms, the world plantations comprised 13 Iowas. U.S. plantations had an extent slightly broader than one Iowa. Worldwide plantations cover 5 percent as much as forests, and in the United States they cover 7 percent as much as total forest. Planting per annum in 2000 was only a small 1 percent to 2 percent of plantation area. In the United States, planting in 2000 proceeded at only 121,000 hectares, or one-eighth the area of Yellowstone National Park, curiously slow.

Another standard for the rate of penetration of genetically modified trees is the planting of genetically modified crops. Because genetically modified crops are annuals, the rate of planting genetically modified crops should be compared to the planting of plantations. Worldwide the annual planting of trees in plantations proceeded only 6.6 percent as fast as the planting of genetically modified crops. In the United States, where two-thirds of genetically modified crops are planted, the planting of all trees in plantations in 2000 proceeded only 0.3 percent as fast as the planting of genetically modified crops, a difference caused at least by economic fluctuations, social anxiety, and technical prowess.

9. MONITORING

Although the expected penetration of genetically modified trees is slow, the worry that “Something terrible could happen” may slow it even more. As with most innovations, achieving the promise of genetically modified trees, or high-yield forestry generally, will require feedback from a watchful public, and we should start watching now. Although experience and research may reduce some unknowns underlying worries, some things that happen are fundamentally unknowable. No level of foresight will anticipate every contingency or confluence of factors. There is no map of the future because no one who has been there ever comes back. So, like good scouts, people should be prepared.

The overwhelming volume of trade dims hope that quarantines will catch all invaders, which will continue mutating and sneaking in. The southern corn leaf blight of 1970 that invaded the United States from the Philippines during wet weather is probably the nearest analogue to genetic engineering gone astray, as it attacked male-sterile corn on which the U.S. corn crop had become heavily dependent. Because quarantines leak, people must monitor vigilantly and innovate in vigilance. Drone planes with spore traps now catch spores of tobacco blue mold and potato leaf blight aloft. Monitoring requires the sequels of reporting and communicating, which the Internet aids, and eventually action. Preparedness to act, whether through chemical control or other means, minimizes danger. U.S. farmers impressively replaced the vulnerable male-sterile corn in one season.

10. CONCLUSION

Human numbers, now 6 billion and heading for 8 billion to 10 billion in this new century, mean we already have a Faustian bargain with technology. Having come this far with technology, we have no road back. If wheat farmers in India allow yields to fall back to the level of 1960, to sustain the present harvest they would need to clear nearly 50 million hectares, about the area of Spain.

Through further intensification, farmers can be the best friends of the forest. Alternatively, they can plow through it. Technology can double and redouble farm yields and spare wide hectares of land for nature. We have confidence that farmers and their partners in the scientific community and elsewhere will meet the challenge of lifting yields per hectare close to 2 percent per year through the new century.

Freed and encouraged by the sparing of farmland, humanity can set a global goal of a 10 percent spread in forest area, about 300 million hectares, by 2050. Furthermore, foresters should concentrate logging on about 10 percent of forestland. Behavior can moderate demand for wood products, and foresters can make trees that speedily meet that demand, minimizing the forest that people disturb. The main benefit of the new approach to forests will reside in the trees spared by more efficient forestry. An industry that draws from planted forests rather than cutting from the wild will disturb one-fifth or less of the area for the same volume of wood. Instead of logging half the world’s forests, humanity can leave almost 90 percent of them minimally disturbed. Social acceptance of the vision of the Great Restoration is key, both for farmers and for foresters.

The essence of the strategy for foresters to achieve the Great Restoration is the same as that for farmers, more bits and fewer hectares. Call it precision forestry. Working precisely, people can spare farmland and spread forests. Precise bits of information called DNA are finally the forester's inevitable and most powerful tool. Would editing a few bytes of the message for a tree to fit human desires do harm or good? Fortunately, foresters have several decades during which to answer by testing and monitoring wisely.

Acknowledgment: We thank Cesare Marchetti and David G. Victor

11. REFERENCES

AUSUBEL, J. H., 2001 The great reversal: Nature's chance to restore land and sea. Technol. Soc. **22**: 289-301.

AUSUBEL, J. H., 2002 Maglevs and the Vision of St. Hubert – Or the Great Restoration of Nature: Why and How, Pp.175-182 in *Challenges of a Changing Earth*, W. Steffen, J. Jaeger, D. J. Carson, and C. Bradshaw (eds.), Springer, Heidelberg.

CHEMICAL & ENGINEERING NEWS, 2001 Data for plastics for 1992-2000. June 25, 2001, pp. 44-51.

FEDKIW, J., 1989 The evolving use and management of the nation's forests, grasslands, croplands, and related resources. Gen. Tech. Rep. RM-175. USDA-Forest Service, Fort Collins, Colorado.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, various Yearbooks. http://faostat.fao.org/faostat/collections?subset=agriculture.

GRILICHES, Z., 1988 Hybrid Corn: An Explanation in the Economics of Technological Change, pp. 27-52 in *Technology, Education, and Productivity: Early Papers with Notes to Subsequent Literature*. Basil Blackwell, New York.

INCE, P. J. 2000 *Industrial Wood Productivity in the United States, 1900-1998.* Res. Note FPL-RN-0272. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin.

INTERNATIONAL SERVICE FOR THE ACQUISITION OF AGRI-BIOTECH APPLICATIONS, 2004 *Global Status of Commercialized Biotech/GM Crops: 2004*, C. James, chair, ISAAA Board of Directors, http://www.isaaa.org.

MARCHETTI, C., 1979a Genetic engineering and the energy system: How to make ends meet. Technol. Forecast. Soc., **15**: 79-86.

MARCHETTI, C., 1979b On energy and agriculture: From hunting-gathering to landless farming. RR-79-10. International Institute for Applied Systems Analysis, Laxenburg, Austria.

MATHER, A. S., J. FAIRBAIRN, and C. L. NEEDLE, 1999 The course and drivers of the forest transition: The case of France. J. Rural Stud. **15**: 650-690.

MYNENI, R. B., J. R. DONG, C. J. TUCKER, R. K. KAUFMANN, P. E. KAUPPI, J. LISKI, L. ZHOU, V. ALEXEYEV, AND M. K. HUGHES, 2001 A large carbon sink in the woody biomass of Northern Forests. Proc. Natl. Acad. Sci. USA **98**(26), 14784-14789.

NATIONAL CORN GROWERS ASSOCIATION, Production, Corn Yield Contest, AA Non-Irrigated Class, http://www.ncga.com/02profits/CYC/profiles/aanonir.htm (accessed March 25, 2005).

SEDJO, R. A., 2001 The Role of Forest Plantations in the World's Future Timber Supply. Forest Chron. **77**(2), 221-226.

UN ECE/FAO, 2000 *Forest resources of Europe, CIS, North America, Australia, Japan and New Zealand (industrialized temporate/boreal countries), contribution to the Global Forest Resources Assessment 2000*. United Nations, New York.

U.S. DEPARTMENT OF AGRICULTURE FOREST SERVICE, 1992 Forest Statistics of the United States, 1992, Washington DC.

U.S. DEPARTMENT OF AGRICULTURE FOREST SERVICE, 1997 Forest Resources of the United States, 1997, Washington DC.

U.S. DEPARTMENT OF AGRICULTURE FOREST SERVICE, 2002 Forest Resources of the United States, Draft RPA 2002 Forest Resource Tables, Washington DC.

U.S. GEOLOGICAL SURVEY, 2004 *Historical Statistics for Mineral Commodities in the United States.* Open-File Report 01-006 http://minerals.usgs.gov/minerals/pubs/of01-006/

VICTOR, D. G., and J. H. AUSUBEL, 2000 Restoring Forests. Foreign Aff. **79**(6): 127-144.

WAGGONER, P. E., 1996 How Much Land Can Ten Billion People Spare for Nature? Daedalus **125**(3): 73-93.

WAGGONER, P. E., and J. H. AUSUBEL. 2001 How much will feeding more and wealthier people encroach on forests? Popul. Dev. Rev. **27**(2): 239-257.

WANN, S. R., and J. L. RAKESTRAW, 1998 Maximizing hardwood plantation productivity in the Southeastern United States—Lessons learned from loblolly pine. In Conference Proceedings, Improving Forest Productivity for Timber, A Key to Sustainability, 1-3 December 1998, Duluth, Minnesota. http://www.cnr.umn.edu/FR/publications/proceedings/papers/Wann-Duluth.pdf

WERNICK, I. K., and J. H. AUSUBEL, 1995 National material metrics for industrial ecology, Resour. Policy **21**(3): 189-198.

WERNICK, I., P. E. WAGGONER, and J. H. AUSUBEL, 1998 Searching for leverage to conserve forests: The industrial ecology of wood products in the United States. J. Ind. Ecol. **1**(3): 125-145.