Biotechnology and Planted Forests: Assessment of Potential and Possibilities

Roger A. Sedjo

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1616 P Street, NW
Washington, DC 20036
Telephone 202-328-5000
Fax 202-939-3460
Internet: http://www.rff.org

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ABSTRACT

This paper addresses the potential impact of the introduction and development of biotechnology on planted forests. It includes a description of some recent innovations in forestry including the use of traditional breeding, and also more recent innovations involving biotechnology, including the development of clonal propagation and the use of modern molecular biology techniques. In addition to describing these innovations, the paper undertakes an assessment of their probable impact on future production of the forest industry, on the global timber supply, and on future markets for timber and wood products.

The paper offers a description of recent innovations in tree breeding and biotechnology, including a discussion of innovations in agriculture that have promise for forestry. This is followed by a discussion of the current role of biotechnology in forestry and an assessment of the various types of biotechnological innovations that could be forthcoming in the next decade and beyond. Additionally, the paper examines the likely effects of biotechnology on the economics of forestry. An estimate is provided for the potential cost savings and/or value increases expected from the various innovations. Using these estimates, a quantitative assessment is made of global potential economic returns to the most immediate and major innovation, the herbicide tolerant trait. Additionally, estimates are made of the potential impact of cost savings realized from this type of biotechnology on future timber supplies in the global timber market.

Key Words: biotechnology, plantation forests, genetic modification, genetic research, economic benefits, transgenic, GMO

JEL Classification Numbers: Q21, Q23, Q16, O32, L73

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CONTENTS

TABLES AND FIGURES

Biotechnology and Planted Forests:
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This paper addresses the question of the potential impact of the introduction and development of biotechnology on planted forests, on the forest industry, and on global timber supplies. Discussed briefly is human use of forest materials through the ages. It includes a description of some recent biological innovations in forestry including the use of traditional breeding and also more recent innovations in biotechnology, including the development of genetically modified organisms.

The paper consists of two major parts. The first offers a description of recent innovations in tree breeding and biotechnology, including a discussion of innovations in agriculture that have promise for forestry. This is followed by a discussion of the current role of biotechnology in forestry. This part ends with a discussion of the various types of biotechnological innovations that could be forthcoming, an estimate of where these innovations are currently in their development, and which specific innovations are likely to become operationally available over the next decade or two.

The second major part examines the economics of biotechnology in forestry. An estimate is provided of the potential cost savings and/or value increases expected from the various innovations. Using these estimates, an assessment is made of the global potential economic returns to the most immediate and major innovation, the herbicide resistant gene. Additionally, estimates are made of the potential global impact of biotechnology in forestry and how it might affect future timber supplies and prices in the global timber market.

1. BIOTECHNOLOGY

Introduction

The domestication of a small number of plants, particularly wheat, rice and maize, is among the most significant accomplishments in the human era. Modern civilization would be impossible without this innovation. Common features associated with plant domestication include high yields, large seeds, soft seed coats, non-shattering seed heads that prevent seed dispersal and thus facilitate harvesting, and a flowering time that is determined by planting date rather than by natural day length (Bradshaw 1999).

Recent decades have seen continuing increases in biological productivity, especially in agriculture. This has been driven largely by technological innovations that have generated continuous improvements in the genetics of domesticated plants and animals. Much of this improvement has been the result of plant improvements that have been accomplished by traditional breeding techniques, through which desired characteristics of plants and animals, (growth rates or disease resistance) can be incorporated into the cultivated varieties of the species in question.

Changes driven by technology, however, are not new. Hayami and Ruttan (1985) have pointed out that in the U.S. most of the increased agricultural production that occurred over the past two centuries before 1930 was the result of increases in the amount of land placed in agriculture. Much of the increased production reflected increased inputs in the form of labor and equipment – animal or mechanical. In Japan, however, where land was limited, substantial improvements in rice productivity were made by careful selection of superior seed. In the U.S. after the 1930s, when most of the highly productive agricultural land was in use, the focus of innovation was directed at plant improvement, which increased land productivity through higher yields. Until fairly recently these improvements were achieved through the use of traditional plant breeding techniques, which gradually increased agricultural yields.

What is Biotechnology?

In its simplest form, biotechnology is the use of micro-organisms (plant and animal cells), to produce materials such as food, medicine, and chemicals that are useful to mankind. By this definition biotechnology comprises any technique that uses living organisms to make or modify a product, to improve plants or animals, or to develop micro-organisms for a specific use (Haines 1994, 1994a). Such activities have been common among humans for a long time and include such activities as brewing alcoholic beverages or the use of traditional breeding techniques for improving food crops and domestic animals.

A more narrow but contemporary definition of biotechnology is "the commercial application of living organisms or their products, which involves the deliberate manipulation of their DNA molecules." Gradually science has evolved its understanding of the chemical coding system, the gene, which is a segment of, and its message is encoded in, the molecule's chemical structure. The gene is a segment of a substance called deoxyribonucleic acid (DNA); the DNA molecule and its message is encoded in the molecule's chemical structure. DNA is passed on from one generation to the next transferring a range of individual traits from parent to offspring. The science of manipulating and transferring chemical instructions from one cell to another is called genetic engineering. When the process involves the transferring of DNA from one organism to another, the result is a genetic modification that would not normally take place in nature—the production of a transgenic organism. This approach has been extremely successful in the development of new drugs, medicines, and pharmaceuticals, as well as in agriculture.

A primary aim of modern biotechnology is to make living cells perform a specific useful task in a predictable and controllable way. Whether a living cell will perform these tasks is determined by its genetic make-up and by the instructions contained in a collection of chemical messages called genes.

This paper begins with biological innovations associated with traditional breeding techniques, but focuses primarily on those associated with genetic modification, including cloning and genetic marking.

Biotechnology Success in Agriculture

Early efforts at plant improvement typically utilized traditional breeding techniques. Traditional breeding techniques have resulted in the development of a large array of "improved seeds" that have generated yield increases in a host of agriculture products. In recent years, however, approaches to increasing agricultural yields have reflected a more sophisticated approach sometimes known as biotechnology or genetic engineering. Techniques have been developed that allow specialized genes to be implanted in plants. These can be naturally occurring or modified genes. The success of genetic approaches for increasing yields and generating desired modifications in agricultural plants is unquestionable. Recent applications of genetic engineering in agriculture have been successful in transferring to agricultural crops a host of desired traits including resistance to disease, insects, herbicides, frost, and so forth.

Genetically engineered products, (gene-altered seeds) have been rapidly adopted in agriculture. There are now several transgenic crops on the market including soybean, cotton, corn, tomatoes, tobacco and canola (approved in Canada). In 1997, global planting of transgenes numbered over 31

Table 1. Area of Transgenic Crops Planted (millions of hectares)

Country	1997	1998
U.S.A.	8.1	20.5
Argentina	1.4	4.3
Canada	1.3	2.8
Australia	0.1	0.1
Mexico	<0.1	0.1
Spain	0.0	<0.1
France	0.0	<0.1
South Africa	0.0	<0.1
Total	11.0	27.8

Source: "Toting Up the Early Harvest of Transgenic Plants," *Science* vol. 282, December 18, 1998, p. 2178

million acres, and sales of genetically altered food crops and ingredients by farms were estimated at $4 billion (D&MD Report 1998). As table 1 shows, the growth in the use of transgenic crops increased dramatically in the U.S. and elsewhere between 1997 and 1998. In 1998, an estimated 25 million acres of transgenic soybean (about one-third of the soybean acreage planted in the U.S.) and 1 million acres of herbicide resistant corn were planted in the U.S. In addition, there were 5 million acres of herbicide resistant and/or insect resistant cotton (out of 13 million acres) and 17 million acres of insect resistant corn (out of 80 million acres). In Canada there were 7 million acres of transgenic canola, out of a total of 14 million acres. (Genetically engineered canola has not yet been approved for the U.S.) The use of transgenics in these crops has increased twice or more over their use the previous year, and expectations are for continuing increases in use in 1999 (*Washington Post*, February 3, 1999). In the U.S. cornbelt, corn transformed to express the *Bacillus thuringiensis* (Bt) protein had a 7 percent increase in yield per acre, translating into an average increase in net return of $16.88 per acre (*Science* 18 December 1998, p. 2176).[1]

Preliminary data for 1999 indicated the total area in transgenic crops in the U.S. has almost doubled that of 1998 to about 40 million hectares.

Newly developed transgenic plants have properties that do not occur in those species in nature. The two most common alterations are herbicide (Roundup) tolerant soybean, corn and cotton, and a genetically altered seed to produce the natural insecticide *Bacillus thuringiensis* (Bt), a type of bacterium that infects and kills insects, which is used in cotton and corn crops. Additionally, transgenic potato plants are now resistant to certain pests (e.g., the potato bug).

New methods of weedy vegetation control have been developed using transgenic plants. Glyphosate (Roundup), for example, is an effective herbicide that has the desirable environmental property of rapidly decomposing into inert compounds. Thus, it can eliminate vegetation on a site without creating traditional environmental problems such as leaving toxic residues in soil and water. In agriculture, glyphosate has been used to treat fields before planting, eliminating all existing vegetation and thus allowing the crop to begin growth with minimal weed competition. However, with ordinary crop plants, glyphosate cannot be used after planting, as it would damage the crop as well as the herbaceous weeds. In response to this situation, an artificial glyphosate-tolerant gene has been developed and introduced into agricultural plants, such as corn and soybeans. Fields

[1] This net return estimate, however, depends on prices remaining unchanged.

with these transgenic plants can be sprayed with the herbicide without damaging crop plants. The main advantage of this approach is lower weed control costs; there is also the potential to reduce total herbicide usage. In addition, yields are often increased, since weedy plant competition has been controlled and there is no inadvertent damage to the crop plants from the herbicide. Similarly, the introduction of a potato bug-resistant gene, which discourages bug infestation (Colorado potato bug), into potato plants has reduced pest control costs and increased potato yields.

Although such transgenic plants have met with opposition in many European countries due to fears that they may be unsafe for human consumption, harmful to the environment, or that they may lead to further costly surpluses (*Science* 1998b), transgenic plants are winning acceptance in countries such as the U.S., Canada, China, and Argentina (*Science* 1998a).

Commodities currently using transgenics find their way into hundreds of foods, such as breakfast cereals, soft drinks, and cooking oils. Obviously, in agriculture, the current use of transgenic products is large and still has the potential for vast expansion.

Although facing resistance in some regions, overall the speed at which agribiotech applications have been commercialized has been quite rapid. In addition, there are important new applications on the horizon, such as making ingestible vaccines for human diseases, and increasing the protein content in milk and potatoes.

Some Concerns

Transgenetic biotechnology has become quite controversial when applied to agriculture (e.g., see *Science* 1998b). However, drug, medicinal, and pharmaceutical applications are essentially without controversy. The nature of the controversy in agriculture (and perhaps similarly in forestry) has developed around two issues. First is the issue of ownership of modified genes and chemicals and the question of how much control biotechnology companies have over their transgenic products after they have been sold. The gene-altered seeds are sold under the condition that their offspring, which also contain the altered gene, will not be used in further plantings. Thus, farmers must return to the seed developer for future seed sources. The rationale is that the company that developed the gene-altered plant has intellectual property rights to this plant throughout the patent period. This argument is buttressed by the fact that development often takes decades and costs hundreds of millions of dollars. The counter concerns are related to two issues. First is that of the disruptions and inconvenience associated with the monitoring of users for compliance with the various provisions of the agreement. (This seems to be the essence in the *Washington Post* article of February 3, 1999.) The second consideration relates to the ongoing controversy regarding the ownership of biodiversity and improved products. For example, are wild genetic resources the property of all of humanity or of the country in which they reside? Are developed biotechnology products the property of the developer or should they be available without royalty payment to all? (See, for example, Sedjo 1992, Kloppenburg Jr., 1988.) This controversy continues to be manifest in the difficulties in interpreting and finalizing the “biodiversity treaty” coming out of the UNCED “Earth Summit” meeting in Rio in 1992. This issue recently returned to the headlines with the inability, once again, of the parties to agree to major dimensions of the proposed treaty.

The second point in the overall controversy relates to health, safety and environmental aspects of transgenic products. These range from concerns about the health effects of foods produced from transgenic products to the effects of transgenic plants on the natural ecosystem. Although there is little or no evidence that transgenic foods are harmful, concerns are raised as to the lack of long-term experience with such products. The health issue is not how the plants were produced (transgenic or traditional breeding) but rather what new proteins the plants are making. Additionally, concerns are expressed as to whether transgenics that "escape" from cultivated fields may interbreed with similar wild plants thereby changing the genetic make-up of some plants and the ecosystem, eventually altering that system in unanticipated ways.

In concept, the biotech issues in forestry appear to be modest compared to those in food. Wood products are not ingested and are unlikely to have any direct human health effects either in the short or long run. In agriculture, an important issue is the extent to which seeds from transgenic plants can be subsequently used for planting. Sterility is a vehicle for allowing the developer to capture the returns on the investment in future planting cycles. This issue is far less important in forestry since the longer time required for tree flowering and the rate of improvement in tree growth and transgenic technology may make the technology embodied in these future seeds obsolete before they can be utilized.

However, there are issues related to the possibility of certain genes escaping from a modified seedling or tree into the natural habitat. For example, what is the possibility that certain genes will escape? Further, if they do, how serious are the likely consequences or the "worst case" consequences? A major reason for introducing a sterility gene into trees is not, as in agriculture, to retain control over future seed sources, but rather to prevent the escape of genes into the natural environment through the tree flowering process.

Although any negative effects of genetic modification in trees appear to be very modest, and much less than in crops, one group has precluded the certification of forests that use modern biotechnology (cloning or genetic modification), from being classified as "sustainably managed" or "well managed" forests. The lack of certification could slow the rate of adoption of biotechnology in forestry.

2. BIOTECHNOLOGY FOR FORESTRY

Background

There is an entire class of plants important to humans, forest trees, which for the most part has not been domesticated. However, the value of forest products is enormous. In 1992, for example, U.S. agricultural crops were worth $111 billion. Timber represented 21 percent of the value of the total crop and the largest commodity group, larger than corn, wheat, or soybeans.

Currently, most of the world's industrial wood is drawn from natural forests in what is essentially a foraging operation. In the past, harvests were taken from forests created by nature as humans simply collected the bounty of nature. Figure 1 indicates how this process has changed over time as humans gradually developed silvicultural technology.

Although forest management began in China as early as 100 BC (Menzies,1992), significant areas of managed forest probably were not common until the middle ages. Planted forests began in some earnest in the 19th century Europe, but not until the middle of the 20th century in North Amer-

Figure 1. Transitions In Forest Management and Harvests

Type	Period
Wild forests	10,000 B.C.–current
Managed forests	100 B.C.–current
Planted forests	1800–current
Planted, Intensively managed	1960–current
Planted, Superior trees, Traditional breeding techniques	1970–current
Planted, Superior trees, Genetic modification	1999?–future

Table 2. Global Harvests by Forest Management Condition Circa 1995

Forest Situation	Percent of Global Industrial Wood Harvest
Old-growth	30
Second-growth, minimal management	14
Indigenous second-growth, managed	22
Industrial plantations, indigenous	24
Industrial plantations, exotic	10

Source: Sedjo 1999.
Notes: Old-growth includes: Canada, Russia, Indonesia/Malaysia;
Second-growth, minimal management: parts of the US and Canada, Russia;
Indigenous second growth, managed: residual;
Industrial plantations, indigenous: Nordic, most of Europe, a large but minor;
portion of US, Japan, and some from China and India;
Industrial exotic plantations: Sedjo 1994;
Second-growth, minimal management: the residual.

ica. The planting of genetically superior stock began about 1970, and serious planting of genetically modified trees is just beginning in parts of the subtropics, New Zealand and South America.

However, as table 2 indicates, even today a large portion of the world's industrial wood supply originates in natural unmanaged forests. In recent decades, however, widespread introduction of tree planting for industrial wood production has resulted in most of the increases in global harvests being drawn from planted forests.

Early industrial tree planting was motivated by the recognition that prices of industrial wood were rising as the availability of native forests for harvest was declining, resulting in rising wood costs. Planted forests were viewed as a supplementary source of wood. Initially, reforestation simply involved the planting of seed collected from existing wild stands. However, tree planting brought the potential to apply management and technology. Planting allowed for the choice of species as well as providing a vehicle for the introduction of technology through improved seed.

The potential of widespread introduction of genetically improved trees can have important economic effects. With increasing yields and shortened rotations, planted forests become increasingly attractive as an investment for producing future industrial wood. The manager can control some important variables, such as choosing a location for the planted forest and the species. Former agricultural sites often are desirable locations for planted forests; generally they are accessible and reasonably flat, thereby lending themselves to both planting and harvesting. Acceptable access often exists via the former agricultural transport infrastructure. A planted forest can also be located in proximity to important markets. Within limits, the manager can choose a species appropriate to the site, which may also have good market access and a reasonably short harvest rotation.

The economic advantages of planted forests have led to their widespread adoption in a number of regions throughout the world; they are having an important influence on global timber supply. Over time, a greater share of the world's industrial wood supply has been and will be coming from planted forests. Planted forests now account for most of the increased global output and their production is replacing the timber formerly provided by native and old-growth forests, which are no longer available for harvest due to political changes, such as the situation in Russia, or policy changes, as have been made by the U.S. National Forest System.

For the future, the role of planted forests will almost surely expand. As pressures increase to devote native forests to other uses such as wilderness, biodiversity preservation, or recreation, less timber harvesting will occur therein and alternative industrial supply sources will need to be developed. Sedjo and Botkin (1997) have argued that intensively managed planted forests provide one of the most promising means to remove harvesting pressure from native forests, thereby allowing other nontimber outputs of native forests to be realized.

The economic attractiveness of planted forest will increase with increasing pressures to remove large areas of native forest from regular timber harvests. Additionally, the financial advantages of plantations that have led to their widespread expansion over recent decades will continue. Finally, with further application of biotechnology developments to forestry, yields and wood quality should rise, even as management and operating costs decline.

Biotechnology for Forest Trees

Current applications of biotechnology to forestry are modest, especially when compared to agriculture or pharmaceuticals. However, the potential for application of biotechnology to forestry and forest plantations is great. It is largely a question of determining which types of applications are likely to have substantial financial returns, and refining the applications and techniques to trees. There have been substantial increases in forest growth and yields due to the application of traditional breeding techniques to produce “superior” trees, which have the ability to grow more rapidly, have greater tolerance to pests, and/or have other desired properties. Cloning approaches, which allow for large-scale, low-cost reproduction of some types of genetically improved germplasma, have been perfected for some species, (certain eucalyptus species) and more are being developed for others. Countries that can utilize eucalyptus species, acacias, and gmelina are most likely to benefit in the near term. Additionally, tropical and subtropical pines such as *P. patula, P. oocarpa, P. radiata* and *P. caribaea* can be vegetatively propagated from seedlings quite easily, much more so than temperate *P. taeda* (loblolly pine), which is commonly planted in the southern U.S.[2] Furthermore, various molecular techniques have been developed that allow for a more efficient identification of genes that convey desired characteristics. Today, forestry is on the threshold of widespread introduction of genetic engineering, which would allow for the transfer of genes and the development of customized transgenic trees with selected desired traits. With cloning techniques, transgenic seedlings can be mass-produced for introduction into plantation forests.

The traits introduced can be of various types. For example, the introduction of an artificially engineered gene that confers tolerance to certain herbicides has already been accomplished, and the potential for herbicide application during the establishment phase for some types of planted forests is substantial. This application is being widely used in certain agricultural crops and its adoption by farmers has been extremely rapid. Today the herbicide tolerance trait is being introduced into new plantings of certain hardwood plantations where weed problems are potentially severe. The presence of this gene, which makes young trees tolerant to the herbicide, allows for the easy, low-cost application of the herbicide early in the establishment cycle without concern that it could injure the crop. This approach not only lowers herbicide application costs, but also allows for more effective vegetative control and potential yield increases.

[2] Personal communication with William Dvorak, North Carolina State University.

Potential of Biotechnology in Forestry

For forestry, biotechnology will probably combine the development of superior trees through traditional breeding techniques and genetic transfer with the ability to replicate improved genetic material on a large scale. Tree improvement using traditional breeding techniques is often viewed as a precondition to effective utilization of sophisticated biotechnology techniques such as genetic engineering. In agriculture there were many decades of seed improvement using traditional breeding techniques before gene transfers were considered. Nevertheless, in some cases gene transfer might be the enabling technology that allows the successful establishment of a hardwood plantation. However, the difficulty of transferring genes varies among different species. In general, hardwoods are more easily genetically improved than conifers.

Additionally, large-scale replication of elite (improved) seedlings is also necessary if the introduction of foreign genes for desired traits is to become commercial. Without a method of low-cost replication of improved material such as cloning, the ability to utilize improved material on a widespread basis is limited. The creation of transgenic trees will be commercially attractive only if a few transgenic plants can provide the basis for large-scale, low-cost propagation. This is likely to be possible only through some type of low-cost cloning, which will allow replication of transgenic plants. However, replication for some tree species has been shown to be relatively easy. For example, improved hardwoods, such as hybrid poplars, are readily replicable through simple vegetative propagation. In the tropics, many species of eucalyptus, gmelina and other tropical hardwood species often are easily propagated through simple root cuttings. It has also been demonstrated that subtropical pines can be cloned; New Zealand is well advanced with techniques for *P. radiata*, and thus replication does not present a problem for genetically altered trees of this type. However, for other species, including many conifers, large-scale replication of improved genetic materials has thus far proven to be difficult and expensive. In this case genetically altered superior trees, which combine traditional breeding techniques and genetic modification, may require long periods of time before they can be replicated on a large scale. In this situation gene transfer could be of limited commercial use due to both cost and time considerations. However, rapid progress in cloning of these species is being made.

Genetic transformation depends on micropropagation and the development of appropriate tissue culture and molecular biology techniques. Transformation for forest tree species is currently constrained at both the species and clonal levels, thereby restricting the selection of biotypes that can be effectively transformed, and sharply limiting the number of elite lines that can be reproduced and genetically modified. However, as improvements occur, the speed at which elite line improvements can be introduced will increase, thereby upgrading the quality of traits in planted forests.

In summary, biotechnological issues in commercial forestry revolve around the scientific and technical ability to develop superior trees, using traditional breeding techniques to take advantage of the variability provided in the species. In general, the clone is viewed as the conduit for commercial development of transgenic trees. Additionally, the ability to massively replicate superior trees in a low-cost way such as cloning, complements the capacity of genetic engineering to insert additional desired foreign genes into superior trees.

Forms of Genetic Research In Forestry

In the tree-growing industry genetic research takes two forms. First is the use of traditional breeding techniques that utilize the variation in the natural population to breed trees with desired traits, sometimes known as superior trees. Second are approaches that rely on various types of biotechnology including microbiology, molecular biology, senomic statistics, and so forth.

Table 3. Gains from Various Traditional Breeding Approaches: Loblolly Pine

Technique	Effect
Orchard Mix, open pollination, first generation	8 % increase in yields
Family Block, best mothers	11 %
Mass Pollination (control for both male and female)	21 %

Source: Westvaco Corporation

Traditional Breeding

Tree improvement most often has relied on traditional breeding techniques like selection of superior (plus candidate) trees for volume and stem straightness, and grafting these into breeding orchards and producing seed orchards. When breeding orchards begin to flower, pollination of selections is artificially controlled, seeds are collected, progeny tests are established, and the best offspring are chosen for the next cycle of breeding. At the same time, selections whose offspring did not perform well in the progeny tests are removed from the production seed orchards to improve genetic quality. In the past, operational quantities of seed from production seed orchards were derived from open pollination. Today, however, more sophisticated large-scale controlled pollination techniques are in place that offer the potential of further improvement of the offspring of two superior parents.

By identifying and selecting for desired traits, breeders can select for a set of traits that can improve wood and fiber characteristics, improve the form of the tree, provide other desired characteristics, and improve growth. These traits are introduced into the genetic base that is used for a planted forest. This contributes to more efficient production of industrial wood and to an improved quality of wood output of the forest.

Thus far, most breeding activity has focused on increasing tree growth and disease resistance. Today, by matching superior seedlings with favorable sites and intensive management, planted forests are generating increased yields over those commonly seen in natural forests. Research is now focusing on improving other desired characteristics in addition to growth rates.

The results of traditional breeding approaches to improve yields are instructive to illustrate the possibilities of traditional breeding (Table 3). For most tree species, the typical approach involves the selection of superior trees for establishment in seed orchards. Experience has shown that an orchard mix of first-generation, open-pollinated seed can be expected to generate an 8 percent per generation improvement in a desired characteristic, such as yield. More sophisticated seed collection and deployment techniques, such as collecting seed from the best mothers (Family Block), can result in an 11 percent increase in yield, while mass-control pollination techniques, which control for both male and female genes (full sibling), have increased yield up to 21 percent.[3]

A variant of traditional breeding techniques is hybridization, which has provided robust offspring by bringing together populations that do not normally mix in nature. As in agricultural products, tree hybrids are often a means to improve growth and other desired characteristics. Hybridization crosses trees that are unlikely to breed in nature, often where parents do not occur together in sympatric populations. These crosses often exhibit growth and other characteristics that neither of the parent species alone can match. In the U.S., for example, several hybrid poplars have shown remarkable growth rates, exceeding those found in parent populations.[4] The same is true for the

[3] Source: Conversation with Westvaco researchers, Summerville, SC.

[4] Growth in hybrid poplar stands is 5-10 times the rate experienced in native forest growth rates (Bradshaw personal communication).

Eucalyptus grandis and *urophylla* hybrid in many parts of the tropics and subtropics. Also, certain types of pine hybrids (pitch and loblolly hybrids), exhibit the resistance to cold weather found in pitch pine and the rapid growth rate of loblolly pine. Also, a hybrid of the *P. carribaea* (Caribbean pine) and *P. elliottii* (slash pine) is known to combine good stem form of slash with the rapid growth of the Caribbean strain.

Molecular Biology

A second major approach to genetic manipulation of trees is the use of molecular biology. Molecular biology has two facets. The first facet is that which may aid the efficiency of traditional breeding programs. One problem with traditional approaches in tree breeding is the long growth cycle generally required by trees, which makes this process very time consuming. Techniques such as molecular biology and molecular markers, which identify areas on the chromosome where genes that control desired traits occur, can accelerate the process and enhance the productivity of the traditional approach. The second facet is the identification and modification of specific genes to affect biochemical pathways and resulting phenotypes. For example, lignin genes can alter the amount, type and form of lignin that is produced.

In recent years molecular approaches to tree selection and breeding have shown significant promise. The molecular approach, although limited in application by its expense, involves genetic material being identified, collected, bred, and tested over a wide range of sites. Rather than simply choosing specific tree phenotypes on the basis of their outward appearance, the molecular approach identifies the areas of the chromosomes that are associated with the desired traits. “Markers” are used to identify the relative position of genes on the chromosome that controls expression of a trait. This approach exploits the genetic variation, which is often abundant, found in natural populations. Molecular markers and screening techniques can be used to examine the DNA of thousands of individual trees to identify the few, perhaps less than a dozen, with the optimal mix of genes for desired outputs. These techniques are currently being applied to the development of improved poplar in the U.S. and eucalyptus in Brazil.[5]

Recent work on hybrid poplar in the Pacific Northwest has shown a 20 percent increase in yields in plantations and an additional 20 percent on dry sites, where irrigation can be applied (east of the Cascade Mountains).[6] Growth rates in these plantations are impressive. Yields are about 7 tons per acre, or about 50 cubic meters per ha, and improvements in yield continue.[7] These growth rates are approximately three times the growth rates of typical pine plantations in the South. Elsewhere in the world, for example Aracruz in Brazil, yields of hybrid eucalyptus are reported to have more than doubled those of earlier plantings.

The second facet is the identification and modification of specific genes to affect biochemical pathways and the resulting phenotypes. For example, the promise of controlling the lignin in trees is dependent on the ability to identify and modify lignin genes, thereby altering the amount, type and form of lignin that is produced in the tree (Hu, Wen-Jing, et al. 1999). As noted, the ease of gene introduction (transformation) varies with different species, generally being more difficult in conifers than hardwoods.

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[5] Personal conversation with Toby Bradshaw, Director of the Poplar Molecular Genetic Cooperative at the University of Washington, Seattle. Also see Westvaco 1997.

[6] Personal communication: Toby Bradshaw.

[7] Withrow-Robinson et al. (1995), p 13.

Clonal Applications

The development of cloning techniques in forestry is important for a number of reasons. First, if superior trees are available, an approach must be developed to allow for the propagation of large numbers of seedlings with the desired characteristics if these traits are to be transferred into a planted forest. Cloning provides a method that allows trees improved by traditional breeding techniques to be replicated on a large scale. Additionally, cloning provides a vehicle for the transfer of desired foreign or artificial genes. Thus, for genetic engineering in forestry to be viable, cloning techniques must be developed.

The ability to use inexpensive cloning techniques varies with species and genus. On the one hand, genera such as poplar tend to readily lend themselves to vegetative propagation. Eucalyptus and acacia also tend to be effective propagators. Other genera propagate less readily. In the pine family, loblolly, and to a lesser extend slash pine, are difficult propagators. However, much progress is being made, making prospects for clonal production very promising in the near term (Barry Goldfarb, North Carolina State University, personal communication). Radiata pine appear to have the best record on this account. Propagation improves when certain procedures are undertaken. For example, using shoots emerging from newly-trimmed clonal hedges increases the probability of successful regeneration. For some species, typically hardwood species, cloning can be as simple as using vegetative propagation properties inherent in the species to accomplish genetic replication. This might involve simply taking a portion of a small branch from a desired superior tree and putting it into the ground, where it will quickly take root (rooted cuttings). Where vegetative propagation is part of the natural process, large amounts of “clonal” material can be propagated via rooted cuttings, the cuttings of which come from “hedge beds.” Here the process continues until sufficient volumes of vegetative materials with the desired genes are available to meet the planting requirements.

For many species, however, the process is more difficult as simple vegetative propagation does not normally occur or occurs only infrequently. Here, “tissue culture” techniques provide the tools to quickly produce genetically engineered plants and clones to regenerate trees with desired traits (Westvaco 1996, pp. 8–9).

Tissue culture broadly refers to techniques of growing plant tissue or parts in a nutrient medium containing minerals, sugars, vitamins, and plant hormones under sterile conditions. It involves a set of techniques known as micropropagation, that is, vegetative propagation that can produce multiple copies of an elite genotype as well as provide a means of introducing novel genes. Approaches include organogenesis and somatic embryogenesis. Typically, plant tissue is placed on a nutrient medium until new buds are initiated on the plant tissue. From these buds, shoots and, ultimately, roots are developed. Somatic embryogenesis is a method of plant tissue culture that starts with a piece of donor plant and forms new embryos. This approach has shown promise for rapidly multiplying some types of conifers and hardwoods. However, for some species[8] micropropagation cloning approaches are limited (Pullman et al. 1998).

Nevertheless, development of clonal approaches to propagation is important to broad utilization and dissemination of genetically improved stock (Westvaco). With tree planting often involving over 500 seedlings per acre,[9] large-scale planting of improved stock requires some method of generating literally millions of seedlings, at a relatively low cost, which embody the genetic upgrading.

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[8] In general, thus far there has been greater success cloning hardwoods, e.g., poplar and some species of eucalyptus, than conifers.

[9] It is estimated that 4 to 5 million trees are planted in the US *every day.*

The costs of the improved seedlings are important in a financial sense since the benefits of improved genetics are delayed until the harvest. With harvests often being 20 years or more after planting, large costs for improved seed may seem difficult to justify financially. However, if the costs of plantings are going to be incurred, the incremental costs associated with planting improved genetic stock are likely to be quite modest and therefore financially justified.

3. THE ROLE OF BIOTECHNOLOGY IN TREE IMPROVEMENT IN COMMERCIAL FORESTRY

With the planting of trees for industrial wood production, there is an inherent incentive for tree improvements. Tree improvements can take many forms (figure 2). Thus far, the most common emphasis of tree improvement programs is increased growth rates, stem form, and disease resistance. Growth typically refers to wood volume growth or yields. Disease and pest resistance traits are also desired to promote or insure the growth of the tree. Resistance traits may be oriented to specific problems common in the growth of particular species or to extending the climatic range of certain species. For example, the development of frost-resistant eucalyptus would allow for a much broader planting range for this desired commercial genus. Other improvement possibilities include, as in agriculture, the introduction of a herbicide-resistant gene to allow for more efficient use of effective herbicides, especially in the establishment phases of the planted forest.

Figure 2. Tree Improvement Programs

Important Attributes:
- *Growth rates*
- *Disease and pest resistance*
- *Climate range and adaptability*
- *Tree form and wood fiber quality*: straightness of the trunk, absence of large or excessive branching, amount of taper in the trunk.
- *Desired fiber characteristics may relate to ease in processing*, e.g., the break-down of wood fibers in chemical processing.

Besides ensuring establishment, survival, and rapid growth of raw wood material, tree improvement programs can also focus on wood quality. Wood quality includes a variety of characteristics including tree form, wood fiber quality, extent of lignin, and so forth. Furthermore, the desired traits vary by end product. Wood quality may involve one set of fiber characteristics for pulping and paper production and another set of characteristics for milling and carpentry. Wood desired for furniture is different from that desired for framing lumber. In addition, some characteristics are valued not for their utility in the final product, but for their ease of incorporation into the production process.

For pulp and paper production there are certain characteristics desired to facilitate wood handling in the early stages of pulp production. For example, the straightness of the trunk has value for improving the pulp and paper product in that less compression associated with straight trees generates preferred fibers. Also, straight trees are important in pulp production since it allows ease of handling and feeding into production systems. Also, paper production requires fiber with adequate strength to allow paper sheets to be produced on high-speed machines. Ease in processing includes the breakdown of wood fibers in processing and the removal of lignin, a compound found in the tree that must be removed in papermaking.

Other wood characteristics relate to utility in producing the final product. The absence of large or excessive branching, for example, influences the size and incidence of knots, thereby allowing for fuller utilization of a tree's wood volume. Also, desired characteristics or properties of final paper products include paper tear strength, surface texture, brightness, and so forth. These are all properties that relate in part to the nature of the wood fiber used. Other features relate to the utility of the wood for use in final wood products, such as straightness, which facilitates production of boards or veneer in solidwood products; wood characteristics related to milling and use in carpentry; wood color; strength; and surface characteristics. In addition, wood fiber is increasingly being processed into structural products such as strand board, fiberboard, and engineered wood products, which have their own unique set of desired fiber characteristics.

In recent years pulp producers have begun to move away from simply producing standardized "commodity" pulp into the production of specialized pulp for targeted markets. For example, Aracruz, a Brazilian pulp company, has asserted that it can customize its tree fibers to the requirements of individual customers. This requires increased control over the mix and types of wood fibers used. Customized products require customized raw materials. However, in the case of Aracruz, thus far the control has been provided through cloning but not genetic engineering.

Biotechnology in Forestry: Some Near-term Potentials

Currently, in the majority of pine species the usual seed source is provided by traditional breeding through open pollination. Additional improvements are likely to be made by extending traditional breeding to controlled pollination. This allows foresters to capture more genetic potential and increase genetic gains. Cloning of the best individuals would, in turn, allow for more gains in plantations. Techniques are available to identify the best progeny, including the collection of clones in the orchard. Also, cloning of improved trees provides for larger amounts of elite germplasm.

Breeding will provide superior growing characteristics for the next generation of improved trees. This approach will probably result in seedling costs rising 250-300 percent. However, since seedlings are only a small portion of the costs required to establish a plantation forest, higher costs associated with superior seedlings will raise establishment costs only about $40 per acre or about 15-20 percent. This innovation and higher cost is projected by some authorities to result in growth increases of at least 20 percent.[10]

The near and intermediate term potential for transgenic operations in pine is less clear. While the introduction of a glyphosate-resistant gene has been very effective in agriculture, it is less likely to be important in pine forestry. Since herbicides currently exist that are effective on weeds but benign to pine seedlings, this common use of transgenic plants is unlikely to be important in pine forestry. Although there may be some potential for certain pesticides to deal with beetles, caterpillars, and the like, there may not be a large market in the absence of serious infestations. Transgenics, however, appear to have the potential to reduce lignin in pines or to make it more controllable in the pulping process. This could be an important innovation, but this development appears to be at least a decade away.

For certain hardwoods, especially poplar, gmelina and eucalyptus, the potential of biotechnology over the next decade or so could be great. The techniques of cloning, including vegetative propagation, are well developed and, together with molecular biology, trees with superior traits can be identified, bred, and replicated via cloning. The costs of cloning operations have tended to be modest. The greatest opportunity lies in the potential to introduce new desired genes into the clone. Unlike pine, hardwood typically faces serious vegetative competition that cannot be addressed very effectively by traditional herbicides without harming the desired plants(the hardwood seedlings). Thus, the use of glyphosate or another herbicide-resistant gene in hardwood plantations, as with many

[10] Personal communication with Barry Goldfarb, North Carolina State University.

agricultural crops, can be expected to generate favorable growth results and reduce establishment costs. Over the next decade or so we can expect widespread introduction and use of a herbicide-resistant gene in hardwood forestry. Furthermore, during that time period there is potential, as with pine, for the introduction of pest- and disease-resistant genes. Finally, there is the potential for the introduction of genes that reduce or make more manageable lignin, and genes that generate more desired wood fiber characteristics. Although some modest progress on these latter two characteristics might be achieved through more traditional breeding techniques, there appears to be greater latitude for modifying fibers through biotechnology.

The Effect of Genetics on Fiber Production

Thus far, tree improvement programs have probably had relatively little effect on fiber production in North America, since there is a lag between the introduction of an improved seedling and the capture of that increased productivity in a harvested tree. In the U.S. most genetically improved trees that were planted during the 1980s will not be harvested until after 2000. However, this is not true of the tropics and subtropics, where harvest rotations are commonly much shorter, often as short as six or seven years.

An anecdote that indicates that tree growers believe that technological improvement in seed stock is important is reflected in the fact that in some places in the southern hemisphere where eucalyptus plantations have been introduced, they have been replanted with superior stock after the first harvest. The original expectation had been that the initial planting would generate three harvests through the natural process of coppicing, a characteristic exhibited by many deciduous tree species whereby the stump of a felled tree will react by sprouting new limbs, which can grow into a tree. Initially the plan was to rely on coppicing in order to save the costs of replanting. However, this has rarely been done. Rather, stumps are treated to prevent regeneration and new genetically superior stock is planted. The rationale for replanting is that the genetic improvement in newly developed superior trees is justification for a new planting, rather than relying on the genetics of the existing tree.

Fiber Farms

In the past decade or so, fiber farms have been introduced in the U.S. and Canada. Fiber farms differ from plantation forests in the degree of management intensity. In the Pacific Northwest (PNW) they are often established on prime agricultural lands or on irrigated arid or semi-arid lands east of the Cascades, but typically not on recently logged land or on marginal agricultural lands that have been neglected. In the Pacific Northwest and British Columbia (BC), forest product firms have established 20,000 to 25,000 ha, largely in hybrid poplar,[11] with rotations of 7-12 years. One advantage of short rotations is that if they are 10 years or less, state law in Washington and Oregon treats the operation as agriculture rather than forestry, and regulations applying to agriculture are typically less stringent than those applying to forestry. In British Columbia the legal requirement for agricultural treatment of a fiber farm is a rotation of 12 years or less. Poplar plantations are common in Europe; however, they tend to occur in small plantings with longer (15-25 year) rotations.

In areas of high annual precipitation, such as west of the Cascades in the -PNW, hybrid poplars tend to be planted on river bottoms and require no irrigation. In dry regions, such as east of the Cascades, poplars are planted on lands that formerly hosted irrigated agricultural crops. In dry regions, drip irrigation is common. Yields are in the 40-50 cubic meters per hectare range on irrigated sites,

[11] The hybrid poplar is using a cross of black and eastern poplar.

and 30-40 cubic meters on non-irrigated sites. It is estimated that there are 20,000 to 25,000 hectares of fiber farms in the PNW and BC, with plans for continued increased plantings.[12] Although the area in fiber farms is very modest compared to the total area of forest, or even compared to the total area of planted forest, it is nevertheless significant and may foreshadow future activities. The anticipated rotation period is as short as 5 years (Withrow-Robinson et al. 1995).

Fiber farms are also being established in the U.S. South and East, motivated by the growing local scarcity of short fiber (hardwood fiber). Hardwoods are increasingly coming into short supply due, in part, to the fact that much of the resource is located on wetter, more inaccessible sites. Fiber farms are being located especially on deep, well-drained sandy soil, often along rivers. Westvaco, for example, has a cottonwood fiber farm in Missouri, which grows hardwood using "fertigation" to increase their growth. Fertigation is a process that delivers precise amounts of water and fertilizer through a drip irrigation system.

The advent of fiber farms brings the possibility of a much faster impact on production since rotations are as short as 5 years. Similarly, industrial forest plantations in the semi-tropics, using eucalyptus, often have rotation periods as short as 6-7 years. With short rotations the impact of new genetic technology embodied in seedlings will have a much more rapid effect on industrial wood volumes.

The reason for the appearance of North American fiber farms is two-fold. First, they have been created to meet an anticipated shortage of short fiber over the next decade or two. Second, they are viewed as a possible approach to dealing with competition expected to come from tropical plantations over the next several decades. Experience from South America, and especially Aracruz in Brazil, has demonstrated that tree breeding and cloning can dramatically improve resource growth and yields.

Types of Biotechnological Innovations

Biotechnological innovations in forestry can be viewed as being of three basic types. First, there are innovations that increase the biological growth of trees. Second are innovations that improve the quality of wood. Wood quality improvements can be such that the final product is more valuable in the market, or they could be of a type that the improved "quality" was reflected in reduced processing costs, as in reduced milling or digester costs. Examples include improving tree form, wood density, fiber characteristics or lignin extraction, and others changes that increase product yields from a given amount of wood. Finally, there are innovations that reduce the costs of forest establishment or management. This includes innovations that allow for lower establishment and management costs for industrial wood forests. These are the types of innovations with which this study is concerned, and especially those that involve the application of modern biotechnology.

Forestry in the Future: Traits and Examples

Gene alteration can result in unique gene combinations unachievable by traditional tree breeding. This allows species to have attributes that would not be possible through natural processes. For example, in concept, frost-resistant genes could be transferred from plants or other organisms found in cold northerly regions to tropical plants, thereby increasing their ability to survive in cooler climates.

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[12] For example, MacMillan Bloedel is planning to plant about 1000 ha annually beginning in 1997. (Personal communication Neil Brett-Davies; memo from S.L. Tisdale 6/18/97).

Table 4. Forest Traits That Can Be Improved through Biotechnology

Silviculture	Adaptability	Wood Quality Traits
Growth rate	Drought Tolerance	Wood density
Nutrient uptake	Cold Tolerance	Lignin reduction
Crown/stem	Fungal resistance	Lignin extraction
Flowering control	Insect resistance	Juvenile fiber
Herbicide		Branching

Source: Context Consulting

These attributes or traits can be characterized as silvicultural, adaptability, and wood quality (table 4). Silivicultural traits would include growth rate, nutrient uptake, crown and stem form, plant reproduction (flowering), and herbicide tolerance.

Growth potential, for example, has a substantial genetic component with rates differing by 50 percent between families or different clonal lines. Traditional breeding approaches are steadily improving elite line yield potentials.

A subset of these traits is found in table 5. These traits include those that are most likely to use biotechnology for further commercial development.

The first four traits of the list in table 5 are traits that, in the judgement of many experts, are likely to be featured prominently in biotechnological innovations in forestry over the next decade.

Planted trees typically require herbicide and perhaps pesticide applications for one or two years after planting. The introduction of a herbicide-resistant gene can reduce the costs of herbicide applications by allowing fewer but more effective applications without concern of the damage to the seedlings. The use of a pest-resistant gene can eliminate the requirement to apply the pesticide altogether. Flowering control allows a delay of several years in flower initiation, non-flowering habit, or sterility. This control may be useful in preventing certain transgenic plants from transmitting genetically modified matter to other plants and/or from migrating into the wild.

As with pest resistance, disease resistance is also important, and the technology for genetic modification for disease resistance is fairly well developed. In New Zealand, for example, the first applications of genetically modified pine are likely to involve "stacking" that is, combining several genetically modified genes, those of pest and disease resistance and flowering control, in the seedling.

Fiber length and uniformity also have a major effect on both wood and pulp quality. Individual trees and families within a species produce different quality fiber. Specific genes associated with these traits can be identified and the desired genes can be transformed into elite materials. These traits can be transformed into increased speed of digesters in pulp mills, saving an estimated $10 per m^3, and superior fiber can increase yields by an amount that raises wood value by another $10 per m^3. (Context Consulting, n.d.)

Table 5: Traits of Interest in Forestry

Herbicide tolerance
Insect tolerance
Flowering control
Disease tolerance
Fiber/Lignin modification
Wood density
Growth
Stem straightness
Nutrient uptake
Cold, wet, drought tolerance

Wood density is known to be correlated to genetic background and has a high heritability. Since breeding has focused on improving growth, not density, the densities of some elite lines have often declined. However, with bioengineering, desired genes from outside the species range can be introduced to improve wood density in elite lines. It is expected that such techniques can improve wood product strength for lumber and increase pulp yields up to 25 percent due to the higher cellulose content per unit volume (Context Consulting, n.d.).

Wood formed during the first 5-10 years after forest establishment (juvenile wood) differs from mature wood. Juvenile wood has a low density, weaker fibril structure, high lignin, and more extractives. Short rotations in high-growth environments have high proportions of juvenile wood. The sharp juvenile-mature transition suggests the intervention of a biochemical trigger. This trigger is likely to be hormonal and may be activated by a single gene. The introduction of such a gene may allow for a reduction in the proportion of juvenile wood. Superior qualities of mature fiber could increase the value \$15 per m^3 (Context Consulting, n.d.).

About 28 per cent of softwood and 20 percent of hardwood dry-weight is comprised of lignin, which through the lignification of wood cells provides the structural strength of a tree. Genes involved in lignin synthesis have been identified and genes that may enhance cellulose production, thereby reducing lignin, are being examined. Lignin reduction accelerates the digester process and reduces energy and chemical input requirements, thereby reducing pulp processing costs. This is estimated to increase the value in pulping by \$10 m^3 (Context Consulting, n.d.).

Well-formed, straight, symmetrical trees provide uniform wood properties. Also, excessive branching can reduce wood value. These traits can be improved today through traditional breeding and genomic approaches that identify candidate genes, and eventually through transgenic procedures .

Traits such as drought tolerance and cold tolerance can expand the species range into lower-cost land, as well as providing significant improvements in growth from trees planted in areas with these conditions. Similar systems are being developed in annual crops, and genes may be transferred from crop or model plants into tree species. Fungal resistance is pathogen-specific, and can address problems such as blue-stain in radiata and heart rot in acacia.

4. THE ECONOMICS OF BIOTECHNOLOGY IN FORESTRY

Recent Work

In an assessment of the effects of research on the productivity of the forestry sector, Hyde, Newman and Seldon (1992) corroborated the work of earlier researchers reviewed by Stier and Bengston (1992) when they found substantial economic returns from a number of research activities related to the development of new products and new technologies in wood processing. In their study, Hyde et al. also assessed the benefits of research in wood growing, such as timber growth and forest management, on softwood timber production in the U.S. South. Newman (1987) had estimated that aggregate productivity in a southern composite of softwood forest inventory plus removal increased at an average of 0.5 percent to 1.0 percent annually over the period 1935-1980. He estimated that about 40 percent of the increase in forest inventory was attributable to increased forestland productivity, presumably due to management. Hyde et al., however, found little positive economic return, even though aggregate productivity of the forest was increasing, and they conclude that “Net present value and the internal rate of return estimates are uniformly poor....” They continue, “Apparently, research benefits in southern softwood growth and management have not led to large social gains” (p. 192).

A major reason for apparent low returns on investments in tree growing appears to be the long delay between the introduction of an innovation on the ground and the capture of financial benefits at harvest. Thus, while a farmer can capture the returns on his investment in improved seed in one season, a forest owner must wait until harvest, which may be decades. Given compound interest, the additional returns must be large to compensate for the time cost of money (the interest rate). This consideration suggests that there are advantages to investments with returns that can be captured quickly. An example here might be the herbicide-resistant seedling. In this case much of the return is captured quickly in the form of lower weed control cost at establishment.

Another reason given by Hyde et al. (p. 218) for the lack of apparent net economic benefits of forest management and tree planting is the large overhang of old-growth forests elsewhere in North America, which serve to limit the amount of price increase that could be expected in the future. Alternatively stated, it makes little sense to invest in activities that produce more rapidly-growing trees when there are large volumes of mature timber that are already available for logging. Thus, the research concluded that economic returns on investment in research in forest management that promoted tree growth was low. This explanation is similar to the findings of Hayami and Ruttan (1985, see p. 115) where they found that, for agriculture in the U.S., investments in yield-improving technologies were not forthcoming until essentially all of the potentially usable agricultural land was in use. Until all of the land available for crops was in use, the returns on investments in equipment designed to extend the area of land that could be planted generated the highest returns. However, once the frontier had disappeared and new crop land was not readily available, returns on investments in research that increased agricultural yields began to be substantial.

There is now some anecdotal evidence found in the market, specifically in the behavior of forest firms in recent periods, that this threshold may have been passed. Many forest product firms are investing substantial sums in tree-growing research efforts, and biotechnology research is common in many intermediate-to-large firms. One interpretation is that the old-growth overhang has largely disappeared, due to both its physical reduction and also due to increasing pressures to establish protected areas that will either not allow timber harvests or allow only limited harvesting (Sedjo 1999a). As less old-growth and native forest is available for logging, the value of fast-growing plantations will be enhanced as will the returns to investments that promote rapid growth. Thus, perhaps the findings of Hyde et al., that research in tree improvement found little support, are not surprising since, until recently, those improvements could not be introduced into wood fiber production in a major way.

Some Estimated Economic Effects

Table 6 lists some innovations believed to be feasible within the next decade or two and suggest possible financial gains. Innovation development costs are not considered.

Economic Impacts of Innovations: Some Examples

All of the innovations noted in table 6 result in a decrease in costs and/or an increase in wood volume or quality. Rates of return can be estimated from many of them. For

example, the 10 percent increased volume due to the cloning of superior pine over a 20-year period is estimated to provide a return of about 10 percent on the additional $40 cost per acre (assuming initial yields of 15 m^3 per ha per year and a stumpage price of $20 per m^3).

Herbicide and weeding cost savings due to the herbicide tolerance trait in Brazil would generate a immediate cost savings of $350 per hectare in establishment costs over the establishment period of two to three years. Obviously, this degree of financial benefit is substantial.

Table 6. Possible Financial Gains from Future Biotech Innovations

Innovation	Benefits	Additional Operating Costs
Clone superior pine	20% yield increase after 20 yrs	$40/acre or 15-20%
Wood density gene	Improved lumber strength	None
Herbicide tolerance gene in eucalyptus (Brazil)	Reduce herbicide and weeding costs saving $350 or 45% per ha	None
Improve fiber characteristic	Reduce digester cost $10 per m^3	None
Reduced amount of juvenile wood	Increase value $15 per m^3 (more useable wood)	None
Reduce lignin	Reduce pulping costs $15 per m^3	None

Source: Context Consulting

The financial impact of biotechnological innovations that reduce pulping costs can also be estimated. The value added from pulping is about $60 per m^3 or $275 per ton of pulp output. If these costs are reduced $10 per m^3, this provides a surplus (or effective cost reduction) of about $47 per ton of woodpulp, assuming wood prices are not affected.

This type of impact would be important to the forest sector. If stumpage wood costs are $20 per m^3, and a mill experiences an increased value of $10 per m^3 due to the superior wood qualities, then the mill ought to be willing to pay, at least initially, a premium of $10 per m^3, roughly 50 percent, for the “improved” wood. Thus, substantial surpluses could be generated initially. However, over the longer term wood producers will respond to the higher marginal wood values with increased production that will lead to falling prices for improved wood.

Furthermore, there is the issue of the cost of introducing technological improvement to the wood grower. The developer is obviously going to want compensation for the development costs. So, in the near term the issue will be how the “surplus” is distributed, among developer, wood producer, and final wood consumer. This will be determined by pricing policies in the context of the market structure that exists. Over the longer term the innovation can be expected to be made available at marginal cost, in which case full net benefits will be captured in the wood market and shared by producer and consumer. At this point the developer’s rights will cease to exist either because the patent period has expired or because subsequent innovations will overtake and reduce the value of the initial innovation.

Advantages to the Firm

The above suggests that cost-saving innovations through biotechnology can come through a variety of innovations and will generate substantial cost savings. However, these estimates were based on the assumption that these innovations do not have a large enough impact to effect the wood price. To the extent that these output generating activities actually do have a significant impact on prices, some of the benefits will leave the firm and be passed on to the consumer in reduced wood prices. Thus the net gains to the firm will be more modest than originally anticipated.

5. ESTIMATING THE GLOBAL IMPACT

It is generally agreed that there is a gradual worldwide shift in industrial wood production from natural forests to plantations (e.g., Binkley 1999). It has been argued that such a trend could have advantageous effects on native forests as harvest pressures are relieved and native forests can be devoted to other purposes (Sedjo and Botkin 1997). The more productive forest plantations can be, the more they can deflect harvesting pressures away from native forests. In this section we will examine the effect of biotechnological innovations on the supply and sources of industrial wood, and the effect on harvests from native forests.

Forestry in the Future

Today, forestry is on the threshold of potentially great increases in productivity. Techniques are already well developed with some species (poplar) for identifying desired genes. Using molecular marker techniques, desired genes can be identified. Trees with these genes can be cloned and cuttings from these trees planted to establish plantations of trees with the desired genes. The process is as follows. 1) Superior trees are identified; 2) a marker identifies the relative location on the chromosome where a desired gene might reside; 3) hedges are grown which create more material from these trees; 4) cuttings are taken; 5) cuttings are planted, which are clones of the superior trees.

Some form of inexpensive propagation of high-value, fast-growing trees in a crop-like setting, along with gene transfer is necessary to make the new technologies economically attractive. Under these conditions, improved trees could be established and maintained at lower costs, thereby decreasing wood costs and increasing wood quality. Clonal forestry or some combination of tissue culture and vegetative cuttings provides a necessary vehicle for the introduction of desired genes, both natural and modified, into elite germplasm. The combination of elite germplasm and low-cost propagation offers the potential to meet future needs for quality raw materials. In nature, plants come from seeds which contain a plant embryo and food materials to sustain the embryo during germination. The use of natural elite seeds for mass planting typically requires many years because of the long life cycles of trees. Consequently, methods of rapid vegetative propagation are preferred. Two approaches are available: cloning and root cuttings.

According to some, clonal forestry, that is vegetative propagation by tissue culture, via organogenesis and somatic embryogenesis, appears to be the most promising technology to multiply the elite germplasm of some desired species (e.g., Pullman et al. 1998). This technique involves creating the right cultural conditions so that embryos can be developed in the laboratory. However, vegetative propagation is difficult with some species using this approach. Additionally, to date no crops, forestry or otherwise, are commercially propagated by embryogensis due to its high cost.

Currently, many tree species are propagated by rooted cuttings including pines (*P. radiata* in New Zealand and Australia). Although rooted cuttings can be used successfully to propagate some angiosperm (deciduous) and coniferous trees, it is difficult to produce large numbers of rooted cutting for some desired species.

Many researchers foresee the utility of a hybrid cutting and tissue culture production system. Such a system might begin with tissue culture to utilize its ability to maintain juvenility of clones in cold-storage (cryopreservation). Field tests and/or DNA markers would identify superior clones. At this point, genetically engineered superior lines could be developed, tissue culture would be used for the rapid “bulk-up” of superior clones, with tissue culture-generated clones then used to establish the hedges from which the rooted cuttings are drawn for planting stock.

Some believe this hybrid system of cuttings and tissue culture offers the opportunity to allow rapid low-cost propagation of elite germplasm. Clearly, the availability of low cost elite germplasm provides the key to successful creation and low-cost introduction of transgenic trees embodying the type of technology that has been so successful in agriculture.

Implications for Future Wood Supply

This section examines two of the most advanced types of transgenic applications for forestry, specifically the use of a herbicide-resistant gene and the use of a Bt pest and disease resistant gene. Table 7 provides estimates of the cost reduction in plantation establishment for the herbicide resistant gene and for the pest/disease resistant gene.

Table 7. Anticipated Value Increases

Herbicide Resistance Benefits:
- $35/acre ($87/ha) cost reduction for fast-growing softwoods
- $160/acre ($400/ha) cost reduction for fast-growing hardwoods

Bt pest resistance Benefits:
- $375 million annually in insect (and disease) tolerance

Source: Context Consulting.

Illustration 1. The Economic Benefits of Herbicide Resistance to Forestry

Forest plantation establishment involves incurring substantial costs in an early period in order to generate larger benefits (discounted) at some future time. High-yield plantation forestry involves plantations with harvest rotations from perhaps as many as 30 years to as few as 6 years. To the extent that costs of establishment can be reduced, net benefits can be achieved. Experts estimate that herbicide resistance would reduce the costs of plantation establishment by an average of about $35/acre for fast-growing softwoods (reduced costs of 15%) and an average of $160/acre for fast-growing hardwoods (reduced costs of 30%). In North America about 4 million acres are planted annually: If 98% (4.9 million) are softwood and 2.0% (0.1 million) hardwood, the potential cost reduction at current rates of planting would be $171.5 million for softwoods and $16 million for hardwoods or a total savings of $187.5 million annually.

Worldwide about 10 million acres of plantation forest are planted per year. If the plantings are roughly 50-50 conifer and hardwood, the potential savings are $175 million for softwoods and $800 million for hardwoods or a global potential savings of about $975 million annually.[13]

Illustration 2: The Estimated Effect on Plantation Establishment and Timber Supply of the Use of the Herbicide-Resistant Gene

Suppose that actual costs to the industry were reduced by the full amount of innovation cost reduction; what increase would be expected in the annual rate of plantation establishment? In this case we examine 3 scenarios: the maximum impact, an intermediate impact, and a low impact.

Scenario A: The total annual rate of global planting is about 10 million ha. Assuming an infinite supply elasticity and a unitary demand elasticity, the estimated impact would be an additional total planting area of 225,000 ha per year. This would be divided evenly between conifer and hardwood. Assuming growth rates on plantation forests average 20 m^3 per ha per year for softwoods and 30 m^3 per ha per year for hardwoods, the result would be an addition to total annual production at harvest of 2.5 million m^3/yr. If these planting increases were realized each year for a 20-year period, about 100 million m^3/yr of additional industrial wood production would be generated annually after 20 years.[14]

Scenario B: Intermediate Impact: Suppose the same conditions obtained as in Scenario A except the supply elasticity is 1.0. In this case a total of 112,500 additional ha planted per year would

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[13] This analysis assumes that the total cost savings to traditional practices would just be offset by the costs associated with using the new roundup ready resistant seedlings.

[14] At the 0.5% annual increase consumption, on a 1997 production/consumption base of 1.5 billion m^3, global industrial wood consumption would be expected to increase about 7.5 million m^3 annually.

Table 8. Scenario Summary

Scenario	Additional Plantings	One year Additional m^3	Twenty years Additional m^3
Scenario A	225,000	5 million	100 million
Scenario B	112,500	2.5 million	50 million
Scenario C	78,750	1.97 million	39.4 million

result in a total increased production at future harvest of 2.5 million m^3/year. After 20 years of planting this would generate about 50 million m^3/yr of additional continuous production.

Scenario C: Estimated Minimum Impact: The assumption is that supply elasticity remains a +1.0, as in Scenario B, but that the demand elasticity is –0.7. In this case we estimate a total of 78,750 additional ha planted per year with an increase in total production at harvest of 1.969 million m^3 per year. After 20 years of planting at this rate the additional continuous production would be about 39.375 million m^3 per year.

Some Implications for Forestry and Natural Forests

The first part of this report suggested that a transition was underway whereby societies that formerly met their industrial wood needs by foraging wood from wild and natural forests are increasingly moving to a cropping mode of wood production, where trees are planted and intensively managed. Biotechnology is part of this transition. To the extent that biotechnology can reduce costs of producing industrial wood or increase the quality of the product, wood from plantations will gain an additional advantage over wood foraged from wild and natural forests. This will continue the long-term trend away from wild and natural supply sources and to production from planted forests, thereby reducing commercial logging pressures on the vast majority of the world's native forests.

6. CONCLUSIONS AND SUMMARY

The application of biotechnology and genetic manipulation to forestry would simply be an additional step in the long-term transition toward producing industrial wood as a crop.

The adoption of transgenic crops in agriculture has been rapid and there is no reason to believe adoption would not also occur quickly in forest plantations.

The first widespread applications of genetically altered plants are likely to be with a herbicide tolerance gene and with insect tolerance Bt applications. The technologies are essentially ready today.

Subsequent innovations are likely to relate to quality-enhancing traits such as fiber characteristics, lignin reduction, and perhaps tree form. Some of these technologies may be operational within the decade, with more in the following decade.

The cost-reducing nature of the herbicide tolerance gene, glyphosate, suggests that its application alone could increase the level of plantation establishment in the range of 78,700 to 225,000 ha annually *over what would have been established* on a worldwide basis without the innovation, thereby adding a net addition to global production of between 1.97 and 5 million m^3 annually.

Finally, the introduction of biotechnology into forestry on a wide scale is simply a continuation of the long-term historical trend away from foraging and toward an increasingly sophisticated cropping mode.

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