Toward Commercialization of Genetically Engineered Forests: Economic and Social Considerations

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Summary

Anticipation of a biotechnology revolution has led to high expectations. However, one area that has been slow to develop is that of tree biotechnology, particularly genetically engineered (GE), or transgenic, trees designed for the production of wood for lumber, paper, and other industrial purposes. The question has been raised as to the adequacy of financial returns in forestry. Although the economic viability of transgenic trees has not yet been adequately demonstrated in the market, this analysis suggests the likelihood of relatively widespread deployment of transgenic trees in the intermediate future, perhaps within a decade or two. It is clear from much of the analysis that GE trees have the potential to provide substantial financial and economic returns under a variety of conditions. This paper examines the nature of financial investment costs as well as some of the differences in investing between long-lived tree products and annual agricultural crops. It identifies and examines the major impediments—economic and other—to the widespread commercial application of GE trees?

Much of the basic research necessary for the development of transgenic trees has already been undertaken and is part of the shared knowledge of the scientific community. The techniques of applying GE to trees are well known and, in fact, being used in laboratories and test plots around the world. Most of the remaining challenges to commercialization are associated with deregulation and public acceptance.

Furthermore, certain regions have inherent advantages that should improve their competitive edge. As part of the process of globalization, forest production has shifted from natural forests to planted forests, where high yields and short rotations create especially favorable conditions. In today's world, the forest industry, including wood production, can readily relocate itself to take advantage of changing comparative costs. And GE trees will tend to enhance the competitive advantage of high-yield plantation forests.

Finally, this paper speculates on future GE tree scenarios. Two countries, China and Brazil, appear to have most of the conditions that would make them early deregulators and commercializers of transgenic trees. Other tropical and subtropical countries also appear to be well positioned to take advantage of GE trees. Although the United States has been a leader in transgenic agricultural crops, deregulation of a transgenic forest tree industry may be sometime

off. As they deal with the obstacles to deregulating transgenics at home, U.S. companies could take advantage of their advanced technology to become leaders in the deployment of this technology abroad.

Many countries, however, have few incentives to plant transgenic trees and indeed may have economic reasons to oppose their introduction. In temperate countries with slow tree growth, for example, the economic gains associated with transgenic trees are likely to be quite modest. These countries may have little to gain by deploying transgenic trees—a position that may be consistent with negative views in some countries toward transgenics plants generally.

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> The economic rationale for investing in genetically modified forest trees for commercial application is not directly apparent at present.
>
> —M.H. El-Lakany 2004

Introduction

Anticipation of a biotechnology revolution has led to high expectations. However, these may be overly optimistic for a variety of reasons (Nightingale and Martin 2004). One area that has been slow to develop is that of tree biotechnology, particularly genetically engineered, or transgenic, trees designed for the production of wood for industrial purposes, such as lumber and paper. Although the financial returns to transgenic biotechnology have been adequate to generate new medicinal and agricultural products, the question is open as to whether applications of transgenic biotechnology will generate innovative forest tree products with sufficient incremental market values to justify the total investment costs. In a recent article, M.H. El-Lakany, assistant director-general, Forestry Department, of the UN Food and Agriculture Organization, raised the question of financial returns in forestry. The reasons for the slow development of genetic engineering (GE)[1] in forest trees include not only issues of environmental concern but also economics. For the reasons examined in this report, the basic financial returns from the commercial application of genetic engineering to forest trees may be lacking for some products in some countries. The paper asks, What are the major impediments—economic and other—to the widespread commercial application of GE trees?

Although the commercialization of transgenic trees has been slow, there has been a large amount of research and development activity around the world (FAO 2004a). Also, at least one transgenic tree has already been commercially deployed: a transgenic papaya *(Carica papapya)*, a fruit tree. This product was deregulated by Animal and Plant Health Inspection Service

[1] The term genetic engineering (GE) is used in preference to genetically modified organism (GMO), since a plant can be genetically modified through traditional breeding practices (sexually) as well as though GE (nonsexual) procedures.

(APHIS) of the U.S. Department of Agriculture, which has been regulating biotechnology in the United States since 1987. The papaya was genetically modified and commercialized specifically to address a disease problem in Hawaii (see Goldman 2003). A second potential commercialized transgenic is a Bt poplar (*Populus nigra,* transformed with the *Bacillus thuringiensis* gene cry1Ac to resist insect damage) that has been developed in China. It was deployed in field-testing as early as 1994 and has been deployed subsequently in further pilot plantings. Authorization by the Chinese regulatory authority permitted the establishment of about one million trees in 2002 on some 300 ha. This was followed by a smaller release with a hybrid poplar clone transformed with both cry1Ac and API in 2003 (Su et al. 2003; Wang 2004).

The actual extent of the commercial deployment of GE poplars in China is unclear, [2] but plantings appear to be oriented toward providing environmental protection services in parts of China that have difficult physical and climatic conditions and where pests have been a serious hindrance to the establishment of forests. Although the distribution of the transgenic as reported has been limited, given the easy vegetative propagation of these hybrid poplars, the engineered gene could be distributed beyond the area of the original plantings (Su et al. 2003).

Biotechnologies used in forestry fall into three main areas: the use of vegetative reproduction methods, including tissue culture; the use of genetic markers; and the production of genetically engineered, or transgenic, trees. Tissue culture and molecular marker applications are most commonly used today (Yanchuk 2001), but this paper focuses on transgenic trees.

Since new developments and the commercial applications of technology typically involve substantial financial investments over time, this paper examines the nature of these investment costs as well as some of the differences between long-lived tree products and annual agricultural crops. In addition to the economic aspects, this paper examines some of the social and ecological considerations associated with the development, deregulation, dispersal, and commercial utilization of transgenic trees in commercial wood production. The paper also touches on some noncommercial wood applications for transgenic trees, such as enhancing the viability of protection forests. The broader implications of the commercialization of GE trees on the global distribution of production are drawn, using a speculative scenario approach.

[2] Ms. Li Shuxin, Policy Division Chief of the Department of Policy and Law, of State Forest Administration, which oversees the use of transgenics in forestry, has advised me that transgenic trees have not yet been commercialized and the extent of their deployment is larger field trails has been overemphasized. Personal conversation, November 10, 2005, Hangzhou, China.

The paper also identifies strengths and limitations faced by selected individual countries in moving toward the commercialization of transgenic trees. In some cases these are technical, climatic and geographic, in other cases they are institutional. Assessing these issues, the paper speculates about which countries are likely to be the early commercial uses of GE trees and how this production might affect them, with a particular focus on the forest and forest products sectors. This approach traces the likely behavior of the various economic agents, assuming that they are driven primarily by market forces and constrained by existing regulations and agreements.[3]

Background

Modern civilization would be impossible without the domestication of a small number of plants, particularly wheat, rice, and maize. Common features associated with plant domestication include high yields, large seeds, soft seed coats, nonshattering seed heads that prevent dispersal and thus facilitate harvesting, and a flowering time that is determined by planting date rather than by natural day length (Bradshaw 1999). However, unlike crops and livestock, domestication is a very recent phenomenon in forestry. Forest trees have only partly been domesticated in the past 50 years, and very few trees are more than one or two generations removed from their wild relatives (El-Kassaby 2003).

Recent decades have seen continuing increases in biological productivity, especially in agriculture. These increases have been driven largely by technological innovations that have generated continuous improvements in the genetics of domesticated plants and animals. Many of the changes have been accomplished through traditional breeding techniques that incorporate desired characteristics, such as growth or disease resistance, into the cultivated varieties or breeds of crops or animals. In the past decade or so, transgenic crops have driven the economic gains and are now well established in large areas of the world (Clive 2004).

Hayami and Ruttan (1985) have pointed out that in the land-abundant United States, most of the expanded agricultural production that occurred during the two centuries before 1930 was the result of increases in the amount of land devoted to agriculture. U.S. grain productivity showed little growth until the 1930s; most of the gains in production were due to

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[3] The study does not make a judgment as to whether the likely market-driven actions are desirable or undesirable, nor does it make any specific recommendations.

labor-saving innovations that allowed more land to come into production through, for example, new equipment and mechanization. However, after the 1930s, when most of the highly productive agricultural land was in use, the focus of innovation was redirected to 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. In Japan, where land is limited, by contrast, Hayami and Ruttan show that substantial improvements in rice productivity began many centuries ago with the careful selection of superior, yield-increasing seed.

During the past 30 years, industrial plantation forests have become major suppliers of industrial wood, gradually displacing that gathered from natural forests. Today, industrial forest plantations constitute only about 2.5 percent of the world's forested area of 3.9 billion ha but account for roughly one-third of the world's industrial wood production (Carle et al. 2002). Since more plantation production has come on stream over the past 25 years, while total global industrial wood production has barely increased, its is clear that both the proportion and the total harvest from natural forest has undoubtedly decreased. Plantations are expected to account for 50 percent of global industrial wood production by 2025 and 75 percent by 2050 (Sohngen et al. 1999). Such a shift would almost surely reduce even further the industrial logging pressures on existing natural forests.[4] Reasons for this change include the improving economics of intensively managed plantation forestry involving enhanced germplasm and large-scale inputs on good sites. Simultaneously, the relative cost of wood from natural forests is generally increasing because of higher costs for extraction and compliance with stricter forest practices regulations, and because of the establishment of more protected and set-aside areas.[5]

In the latter part of the 20th century, forestry began an important transition from a wild resource, which typically had been foraged, to a planted crop that is harvested periodically (Sedjo 1987,1999). This transition has also involved a substantial restructuring and relocation of the forest products industry, which is part of the broader worldwide phenomenon of globalization (Bowyer 2004). For the forest industry, this transition is, no doubt, still in its infancy.

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[4] See Friedman and Charbley (2004) for a critical discussion of this impact.

[5] For example, harvests in 2003 from U.S. national forests were less than 18 percent of what they had been 15 years earlier, reflecting the declining use of these natural forests for timber production purposes.

Globalization can be thought of as the logical extension of international trade. International trade allowed goods produced in one region to be transported and traded in another; globalization now extends this model to other dimensions. Not only is the trade of goods made easy, but so too is the flow of capital and investment. Whereas open trade permitted countries to produce and export goods in which they had a comparative advantage, often based on their endowments of natural resources or capital investments, globalization allows capital investments to flow to regions where they are particularly productive. In forestry, these investments include the forests themselves in the form of investments in plantation forests.

Even as this transition occurs, many wild trees are gradually being domesticated. As in agriculture more generally, economic incentives for investments in plant domestication, breeding, and plant improvement require that the investor capture the benefits of the improvements and innovations or that policy provide for publicly financed research. In recent decades, traditional breeding techniques have been practiced in forestry as they have been for some time in agriculture. Early plant improvements involved identification of individual trees with desired traits and attempts to breed offspring that would be "superior" trees. The first GE forest tree was poplar, in 1986 (Parsons et al. 1986). Since the early 1990s, modern biotechnology, including genetic engineering, has been applied in earnest in forestry.[6]

In most countries, transgenic plants are automatically regulated and require formal deregulation before they are authorized for unrestricted commercial use. In the United States, for example, by 2000 a relatively large number (124) of introduced traits of transgenic trees had been entered into the regulatory process for field-testing prior to application for commercial approval (McLean and Charest 2000). However, thus far only one transgenic tree species (papaya, a fruit tree) has been deregulated in the United States and authorized for commercial release.

The benefits from the introduction of biotechnology to forestry are potentially large and varied. The economic benefits of transgenics will ultimately be found in the form of lower production costs and therefore increased availability and affordability to consumers of wood and wood products. This will probably be achieved both by producing wood with traits that lower the costs of processing and by producing wood with superior characteristics.

[6] See Sigaud (2005) for a recent assessment of the global situation with transgenic trees.

Environmental benefits of using transgenics for commercial wood production can be found in reduced requirements for chemical pesticides. Additionally, the increased productivity of planted forests may free large areas of natural forest from pressures to produce industrial wood, perhaps thereby providing more biodiversity and other values. Also, benefits from the application of phytoremediation—cleanup technology that exploits the actions of plants and their associated microbes to alleviate hazardous soil contamination—could be substantial.[7] Trees, including particular types of poplars, are capable of removing and degrading a number of organic pollutants, such as those that cause groundwater pollution (e.g., see Doty et al. 2005). Transgenic modifications of selected trees should make this process much more effective.

Other environmental opportunities involve the application of biotechnology to habitats under pressure from exotic pests or diseases, as with the American chestnut tree (*Castanea dentata*) in the United States (Bailey 1997). Also, through biotechnological improvements, trees can be modified to grow in previously unsuitable areas, such as arid lands or saline soils, thereby providing missing watershed protection and other environmental functions. Such uses could not only increase wood outputs but might also promote increased carbon sequestration in forest sinks, thereby contributing to the mitigation of the global warming problem (IPCC 2001).

Unlike most agricultural products, GE trees are subject to fewer concerns for direct health or safety effects, although cellulose is occasionally used as filler in food products. There are, however, environmental and ecological concerns related to genetic flows that might occur between transgenic and wild trees, and the potential implications of these genetic transfers for the natural environment.[8]

Regulations regarding the development, deployment, and use of transgenics differ. Today, the two major markets for agricultural crops, the United States and European Union, have different—and sometimes shifting and unclear—regulations for genetically modified products (Pew 2005). For example, labeling requirements and limits on foreign genetic material in food products are often unclear. In many cases facilities to enforce these guidelines do not exist, and thus these measures may be interpreted to discriminate against foreign products (UN 2003).

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[7] For a generally positive view of this potential, see Strauss and Bradshaw (2004).

[8] For an alarmist's view of the possible negative consequences of genetically engineered trees, see Lange (2004).

Finally, the ownership and property rights issues in forestry are in some ways distinct from those of agriculture and so raise somewhat different questions (see Bryson et al. 2004). Intellectual property associated with biotechnological innovations may be easier to control than in typical seasonal agriculture because of the longer maturation of forest trees: it takes years for conifers to reach maturity and produce seeds. On the other hand, for trees that are easily reproduced vegetatively (cloned), the ability to maintain ownership of the current technology could be quite difficult.

Financial Basics

This section identifies and examines some aspects of the types of investments required for tree innovations. Typically, costs in the early years associated with the investment are followed by revenues or returns generated by the investment. The question of financial viability is whether the returns in the later years are sufficient to justify the earlier investment costs. Since the costs and returns occur at different points in time, a discount rate is used to "normalize" the costs and returns to a common time period. Various investment criteria, including benefit-cost ratios, discounted present values, and internal rates of return,[9] can be used to determine whether the investment generates a stream of earnings through time that, adjusted by the appropriate discount rate, equal or exceed the stream of discounted costs.[10] This relationship determines whether the investment generates a net positive return through time when gross costs and returns are adjusted by the discount rate—that is, when the time costs of capital are considered. Of course, higher returns are preferred to lower returns, other things being equal. The general rule is as follows:

> Cost of the investment $<$ Sum of the value of the benefits, when all costs and benefits are adjusted for time by the discount rate

Alternatively, one might require that an investment generate a rate of return in excess of some minimum. This is the internal rate of return (IRR) criterion. For example, the investor might require that an acceptable investment generate an internal rate of return of at least 10 percent.

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[9] Whereas the benefit-cost ratio and the discounted present value use a predetermined (exogenous) discount rate, the internal rate of return solves for the discount rate that equates intertemporal costs and benefits.

[10] The literature has determined that the discounted present value is the most accurate criterion, although the various criteria are often used almost interchangeably.

The above formulation suggests that returns in the near future are preferable to returns in the distant future. Figure 1 presents the components of two comparative investments with different time dimensions. For example, suppose an investment costs $100 in the initial year and generates outputs worth $10 each year for 20 years. The rate of return on this investment would approach 10 percent.[11] This is the rate of return on the incremental annual crop improvement due to GE innovations.

Now suppose a second investment also costs $100 initially and generates outputs that could be worth $10 each year, but the cumulative outputs and associated revenues can be collected and marketed only at harvest in year 20, when the total accumulation is worth $200. The rate of return on this investment would be approximately 3.9 percent. This would be the rate of return generated by an improved GE tree using a 20-year harvest rotation.

Figure 1. Annual and Cumulative Benefit Collection

Annual crop: Investment of 100 value units (e.g., $) generates incrementally 10 value units of outputs each year for 20 years. Internal rate of return (IRR) approximates 10 percent.

Tree rotation of 20 years: Investment of 100 value units generates incrementally 10 value units each year to a cumulative 200 value units at harvest after 20 years. IRR = 3.9 percent.

Note that even though the total cumulative return of both investments was $200, the rate of return declines markedly because of the delay in the collection of revenues. The waiting time is a critical element to determining the rate of return and thus the financial viability of an investment. Because of the long-lived nature of most trees and the time discounting common in financial assessment, trees have certain financial disadvantages compared with annual agricultural crops. Foresters have understood the financial disadvantages of long-rotation forestry since at least 1849, when Martin Faustmann first published his classic formula (see 1995 reprint). The model implies that for the same initial investment cost, many short-cycle (annual) GE crops could generate acceptable financial returns, whereas tree crops delivering the same

[11] If the returns continued in perpetuity, the IRR would equal 10 percent over that infinite time period.

total value, but delayed, might not be financially viable. Thus, the hurdles are more difficult for long-lived trees than for annual crops, other things being equal.

A second implication that follows from the first is that shorter tree rotations are financially preferable to longer rotations, other things being equal. Thus, it is not surprising that most tree plantations focus on species with short rotations and that tree improvement innovations are directed at increasing tree values or decreasing costs.

Finally, it should be noted that despite the disadvantage of the long rotation time, planting trees has been demonstrated to be a financially viable investment in many situations.

Investments in Improved Forest Trees

Investment stages. Starting with a stock of basic research knowledge, one can think of the development of improved tree products as involving several types or stages of investments.[12] Two types of innovations are examined: innovations generated through traditional tree-breeding techniques, and tree innovations achieved through genetic engineering. The development and successful commercialization of a transgenic tree involve some additional investments, such as investments in deregulation, that are not required for trees improved through traditional techniques. Also, forestry entails investment time costs that are not required for annual agricultural crops.

Table 1 lays out four investment (cost) stages in the development of a new transgenic forest tree: the initial development costs, deregulation costs for a transgenic, distribution costs, and time costs to the grower between planting and receiving financial returns. If the improved tree is transgenic, in addition to deregulation costs, one might expect some additional distribution costs to overcome the GE stigma[13] that may be present in many markets.

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[12] Traxler (2005) distinguishes between targeted technology research, where very large funding is required (leaving this activity to only the larger firms and/or government), and spillover benefits from earlier research, which can be achieved at much less cost by drawing on the earlier research findings. Here we refer principally to spillover research

[13] "Stigma" refers to a decidedly negative view of the product by a significant portion of potential consumers. The term denotes nothing about the cause or justification of that attitude. Stigma is reflected in a reduced demand for the product and perhaps political action against the product and/or process.

Table 1. Investment Stages for Conventionally Bred and Transgenic Trees

Stage 1	*Stage 2*	*Stage 3*	*Stage 4 (unique to trees)*
Development costs	Deregulation costs (for transgenics only)	Distribution costs (including stigma costs unique to transgenics)	Time costs: planting to market

Investment costs for an innovative transgenic tree typically consist of (1) the development costs for the new product, such as the herbicide-tolerance gene inserted in a plantation tree species; (2) the cost of applying for and obtaining deregulation for the new transgenic product (in most countries, a transgenic plant is automatically a regulated article requiring deregulation for commercial use); (3) the costs of advertising, marketing, and distributing the new tree, including overcoming public opposition to transgenics; and (4) the time costs between when the tree is planted and when these benefits are captured and monetized—an issue common in forestry. Note that stages 2 and 3 involve additional costs for a transgenic product but not for a tree improved through traditional breeding.

That suggests that, other things being equal, the conventional tree would be preferred by the developer, since investment in it avoids the costs of deregulation and stigma. Of course, other things are not always equal. In addition, while stigma may be an important cost, it need not be prohibitive. Despite substantial deregulation and stigma, major GE crop innovations have successfully been commercialized in many countries. Moreover, genetic engineering often allows transformations to be accomplished at lower investment development costs than would traditional breeding. Perhaps more importantly, asexual GE allows transformations to be executed that cannot be accomplished using traditional sexual breeding approaches (Carson et al. 2004). Hence, despite the extra investment costs, certain products are possible only using the GE technology.

Product development costs. The level of investment in tree biotechnology is difficult to estimate, and product development costs obviously vary with the particular product. For conventional tree breeding using a well-known species with a short juvenile phase, the costs of developing a new forest tree have been estimated at about $400,000 and require 15–20 years (Fenning and Gershenson 2002).

For larger, more complicated operations, the costs are higher. It is estimated that the New Zealand Forest Research Institute spent about US$20 million (1989 dollars) on GE tree research and development over the period 1959–1989. Also, while somatic embryogenesis research is directed only at pine, this research in New Zealand has been estimated to cost about US$30 million over a 10- to 15-year period (Carson et al. 2004, 30).

For transformations where the genes with the desired traits are not found in the species of interest, a transgenic approach is required. Transgenic approaches may facilitate a more precise transfer of desired genes (since no irrelevant genes are inadvertently transferred to the new plant, as they would be in traditional breeding).[14] Finally, some transgenic approaches may compress the time involved in developing a new tree. Approaches that show promise for reducing the period required to improve long-lived plants like trees include genetic marking, which could identify the genes associated with aging, and GE transformations, which might reduce the time to maturity (Strauss et al. 2004).[15]

Market considerations. The total return to the developer depends on the price received in the market and the volume of sales—and thus on the size of the market for the innovation. For a major annual crop, the maximum potential market would be all the seed required for planting a given crop each year.[16] As a transgenic innovation is adopted by growers, sales increase to some maximum set by the size of the market. Other things being equal, a large market offers greater potential for generating the large revenues needed to allow the developer to cover the costs of the investments and earn a positive return.

The potential market in forestry is probably much smaller, since even fast-growing plantation trees are usually planted in harvest rotations of 6 to 30 years. Thus, new seed stock for a site is required only once every one-half to three decades, making the annual market associated with a given land area much smaller than for annual agricultural crops. Additionally, in a dynamic industry the subsequent seed stock offerings will probably be improved over the initial transgenic stock. Because the developer may have only one sale per innovation per site, the opportunity to generate returns to cover the investment costs of the innovation is limited.

For an innovation to be financially viable, it must provide enough incremental benefits to allow it to be priced attractively to the grower and still allow net benefits to be captured by

[14] See Hancock and Hokanson (2004) for the argument that a transgenic is much less likely to become invasive because only a small number of genes have been modified and these are known.

[15] For example, recent work with *Arabidopsis* LEAFY (LFY) has been demonstrated to induce early flowering in transgenic trees (Rottmann et al. 2005).

[16] Traxler (2005) argues that, because of the large numbers of varieties for most seed crops, these individual markets are much smaller than often believed.

the developer. Thus, the innovation must provide enough cumulative financial returns to cover the costs of the firm's investments associated with this innovation and generate a reasonable rate of return, as well as provide some financial advantages to the farmer.

It might be noted that in a corporate restructuring in the late 1990s, Monsanto decided to focus on the application of its transgenic technology to major crops and eliminate efforts in minor crops, including forest trees, while making the existing tree technology available to third parties for further development and commercialization. We can infer that the financial returns for forest trees were less attractive than for major crops, probably in part because of the relatively small size of the potential market.

Potential High-Return GE Tree Innovations

Forest biotech industry. The early transgenic work in forestry was done by large biotech firms, such as Monsanto. Today, in the developed countries, large biotechnology companies are largely out of forestry, and most innovations are being undertaken at universities, private biotech organizations, or large forest products companies,[17] sometimes in cooperation. For example, a major private tree biotechnology research company in the United States is owned by several large forest products companies that have pooled their transgenic research efforts (Sedjo 2004). Also, university programs are often funded by the forest industry. Although traditional breeding activities continue to be undertaken by large individual forest industry firms, in some parts of the world, particularly China, governments actively support transgenic tree research (Wang 2004). More generally, there appear to be differing views in the forest industry on the financial viability of transgenic trees, with some firms financing research and others observing events from the sidelines.

Improved trees and transgenic innovations. In general, the focus of transgenic tree development is to reduce per unit production costs by either lowering wood costs or improving a quality dimension. The usual approach combines traditional tree-breeding improvements with transgenics. Traditional breeding is usually directed to providing the best basic tree, often

[17]Whereas the "green revolution" in crops was driven by research funded and undertaken by governments and the international governmental community (for example, the Consultative Groups system), the research required for the "gene revolution" comes largely from the private sector (FAO 2004b). This is true for GE in forestry also.

with a focus on growth and yield.[18] GE is then used to add one to several desired traits to this already-superior tree. Most of the effort today is directed at producing wood fiber and lowering delivered wood costs or reducing mill processing costs for pulp and paper production.

Transgenic trees offer the potential of producing trees that are more valuable because of their silvicultural features, environmental adaptability, and wood characteristics (Table 2). Certain wood quality traits, for example, are desirable in themselves: density improves strength, and lignin reduction decreases processing costs. Tree form improvements also lower processing costs, and disease and pest resistance reduce management and protection costs. Tolerance of drought or cold allows commercial forests to be established in previously unproductive areas, and flowering control can reduce risks of gene escape and thus relieve stigma concerns and costs.

Table 2. 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 and stem form	Fungal resistance	Lignin extraction
Flowering control	Insect resistance	Juvenile fiber
Herbicide resistance		Tree form, branching

Table 3 lists five promising biotechnological innovations with estimates of their likely benefits. All five involve specialized transgenic transformations to impart traits that involve no additional operating costs, other than seedling costs, which would be expected to be higher since they would incorporate the transgenic technology. Thus, for the five listed innovations, the transgenic tree would provide benefits either through reduced mortality and/or tending costs during the growing cycle (as with reduced weeding costs) or in the form or increased of higher-quality final outputs (as with more desirable wood characteristics).[19]

[18] In part this approach reflects the inability to identify a limited number of genes that are responsible for growth. Apparently, the growth rate is the controlled by a host of genes working in a complicated interrelated manner.

[19] Many of these traits could, in principle, also be obtained using traditional breeding.

Table 3. Possible Financial Gains from Future Biotech Innovations

Innovation	*Benefits*[20]	*Potential savings or gain*	*Operating costs*
Increased wood density	Improved lumber strength		None
Herbicide tolerance in eucalyptus	Reduced herbicide and weeding costs	\$350 or 45 percent per ha	None
Improved fiber characteristics	Reduced digester cost	\$10 per m^3	None
Reduced juvenile wood	Increased value (more usable wood)	\$15 per m^3	None
Reduced lignin	Reduced pulping costs	\$15 per m^3	None

Source: Context Consulting.[21]

The value of these benefits is quantifiable when processing cost reductions (e.g., decreased digester costs) or the market value of product quality improvement (e.g., a premium price for improved lumber) is known. Thus, if the value of an innovation is captured in a lower cost or a high market price, it would be reflected in higher market prices for the transgenic seed or seedling.

In addition to transgenic innovations, an important advance would be an easy, low-cost technique for vegetatively reproducing conifers, to make transgenic innovations in pine trees commercially viable. A superior pine clone would offer two advantages. First, it would allow the highest-yielding improved trees to be reproduced and utilized directly, undiluted by breeding, as clones (Pullman et al. 1998). Clones of traditionally improved trees could then be planted en masse. Second, cloning would allow low-cost mass commercial seeding production of transgenic pine. Thus, the low-cost pine clone is an “enabling” and probably necessary innovation for the commercialization of transgenic pine. However, at this time, clonal

[20] The cost savings experienced by the tree grower independent of any additional costs for the improved seed or seedling.

[21] Context Consulting provided information on potential innovations and their likely cost implication based on the best judgment of a panel of experts circa 1997.

technology for pine is still relatively expensive and makes plantation establishment with clonal seedlings costly (Table 4).[22]

Table 4. Superior Pine Clone: Costs and Benefits

Innovation	*Benefits*[23]	*Operating costs*
Cloning superior pine	20 percent yield increase after 20 years	$40/acre or 15–20 percent cost increase at establishment

Source*: Context Consulting.*

Crude estimates of potential market size for selected innovations. Industrial wood production in the world has been about 1.5 billion cubic meters annually for most of the past two decades. Of this, roughly one-half of the wood volume, about 750 million cubic meters, is used in the production of pulp and paper. Removing lignin costs the pulp and paper industry an estimated $20 billion annually (Mann and Plummer 2002).

A processing cost reduction of $10 to $15 for each cubic meter of wood processed (Table 3) could result in a worldwide cost savings approaching one-half of the total, or $7.5 billion to $11 billion annually. This estimate is an upper limit, of course: large volumes of wood will continue to come from natural forests and nontransgenic plantation trees. Nevertheless, just replacing the current nontransgenic planted trees—about 34 percent of current wood harvest—with trees genetically transformed to provide fiber that can be processed at low cost could generate worldwide savings of $2.5 billion to $3.5 billion annually.

Other transgenic innovations have great savings potential as well. An earlier estimate of the potential market for herbicide-tolerant trees also found a potentially large worldwide market, of up to $750 million to $1 billion annually (Sedjo 1999).

The point here is not to provide a precise estimate of market size. Rather, it is to demonstrate that even though trees are not an annual crop, innovations have fairly short lives, and the actual market may be only a fraction of the potential market. Nevertheless, the market

[22] Elite pine clones have recently become available on a limited commercial basis in the North America (CellFor meeting in Atlanta, Georgia, May 2004; also see Mann and Plummer 2002).

[23] The actual cost savings experienced by the tree planter in the near term will depend on the portion of innovation's savings to be captured by the developer and that passed on to the grower.

could be quite substantial. Innovations in these markets have the potential of generating millions, and indeed billions, of dollars in annual cost savings.

Biotechnology Techniques and Approaches

Expanding on Yanchuk's identification of biotechnology in forestry in the introduction, El Kassaby (2003) has subdivided biotechnology into five major categories: (1) markers; (2) propagation and multiplication; (3) functional genomics; (4) market-aided selection and breeding; and (5) genetic modification. Although this paper focuses largely on the fifth—the production of genetically engineered, or transgenic, trees—the following section briefly discusses some of the other important technologies.

Cloning and vegetative reproduction. Vegetative reproduction comprises a broad range of techniques involving the manipulation of tissue to reproduce live specimens, which are planted and in turn produce new plants. Tissue culture broadly refers to clonal techniques of growing plant parts in a nutrient medium containing minerals, sugars, vitamins, and plant hormones under sterile conditions. However, as noted earlier, for some tree species, cloning approaches have been limited. In general, there has been far greater success cloning hardwoods, such as poplar and some species of eucalyptus, than conifers.

The development of reproductive techniques, including cloning, is important in forestry for a number of reasons. First, once superior trees have been bred, large numbers of seedlings with the desired characteristics must be propagated if these traits are to be transferred into a planted forest. With tree planting often involving more than 1,000 seedlings per hectare,[24] large-scale growing of improved stock requires some method of generating literally millions of seedlings at a relatively low cost. Minimizing the costs of the improved seedlings is important financially, since the benefits of improved genetics are delayed until harvest—often 20 years or more after planting—and thus high costs for improved seed may seem difficult to justify. However, the incremental costs associated with planting improved genetic stock are likely to be modest. Additionally, and very relevant for this report, the clonal technique provides a potential vehicle through which desired foreign or artificial genes can be transferred and propagated inexpensively. Thus, for genetic engineering to be commercially viable in forestry

[24] It is estimated that four million to five million trees are planted in the United States every day.

applications where vegetative propagation is difficult, low-cost cloning techniques are a prerequisite.

The ability to use inexpensive cloning techniques varies with species and genus. For some hardwoods, such as poplar, cloning can be as simple as using the vegetative propagation properties inherent in the species to accomplish the genetic replication. This might involve taking a portion of a small branch from a 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," which provide bulk genetic material from which commercial seedlings can be generated. Here the process continues until sufficient material with the desired genes is available to meet the planting requirements.

Eucalyptus, poplar, and acacia tree types tend to be effective propagators. Other genera propagate less readily. Many species in the pine family, such as loblolly and to a lesser extent slash pine, are difficult propagators. Radiata pine *(Pinus radiata)*, common in plantations in New Zealand and Chile, appears to have the best record to date on this account, although substantial progress is being made for pine regeneration in North America using a technique called somatic embryogenesis. Propagation improves when certain procedures are undertaken. For example, using the shoots emerging from newly trimmed clonal hedges increases the probability of successful regeneration. For many species, however, the process is more difficult, as simple vegetative propagation does not normally occur or occurs only infrequently. Tissue culture techniques can quickly produce genetically engineered plants and clones to regenerate trees with desired traits.

Herbicide tolerance. Planted trees typically require herbicide and, in some cases, pesticide applications for one or two years after planting. The introduction of an herbicide-tolerance gene can reduce the costs of herbicide applications by allowing fewer but more effective applications without damage to the seedlings. The use of a pest-tolerance gene can eliminate the need to apply the pesticide altogether. Disease resistance is important, too, and the technology for genetic modification for disease resistance is fairly well developed. In New Zealand, for example, the first applications of genetically modified radiata pine are likely to involve "stacking"—that is, combining several genetic modifications, perhaps for both pest and disease resistance—in the same seedling. Flowering control is viewed by the industry as an important priority, in part to improve overall social acceptability; although it has been difficult to achieve in conifers, trials with low-lignin deciduous trees have already been undertaken by Aracruz Cellulose in Brazil (Hall 2000) and elsewhere.

Not surprisingly, the use of the herbicide-tolerance gene, which is common in crop agriculture, is among the GE innovations under development for deciduous trees. This innovation has some attractive features that would improve the return on investment: the gene has been developed for various crops, many of its properties are known, and it would not be new to the environment or the public. Thus the actual development costs to apply this technology in forestry are likely to be lower than if it were developed *de novo*. In addition, in concept the deregulation costs could be lower than if the regulators were unfamiliar with the gene. Also, the broad distribution costs could be lower, since it will be pointed out to the public that this is not a new genetic modification.

Finally, a unique advantage is that of timing. Whereas many of the proposed GE innovations require that the user wait the full harvest rotation to capture the monetized benefits, the herbicide-tolerance gene is used during the first two years of plantation establishment to control weeding. One estimate is that for certain deciduous species in one country, its use could save up to $350/ha in reduced weeding costs (Sedjo 1999). These financial benefits come early in the growing cycle.

Insect pest resistance. The insertion of the Bt gene, which expresses an endotoxin from *Bacillus thuringiensis*, provides resistance to certain insect pests. Like the herbicide-tolerance gene, the Bt gene is expected to provide many of its benefits early in the rotation cycle, where it is anticipated to be a cost-saving substitute for pesticides. In general, transgenic Bt trees are developed to reduce the costs of pesticides in forests with serious insect pest problems. China, where insect defoliators are a serious problem, has developed a Bt poplar that is reported to have reduced defoliator damage up to 80 percent (Hu et al. 2001). Subsequently, China deregulated[25] and deployed a limited number of commercial transgenic poplars. It appears that the use of Bt poplar is primarily intended for environmental protection in parts of China where tree growing is often difficult and pests are a serious problem. Thus, the benefits would be largely nonindustrial and accrue in the form of reduced erosion, improved water flows, and general land and vegetation rehabilitation. Without the Bt transgenic tree, these protection forests might not be established.

[25] See Pachico (2003) for an international comparison of the GE regulatory approach to transgenic crops that includes China.

Disease resistance. Genetic engineering offers a number of ways to apply to trees the knowledge of disease resistance and cross-protection gained from crop plants. The most highly developed example of viral resistance in trees comes from papaya, where papaya ringspot virus is a major problem. Using biolistic transformation, a virus-coated protein gene was inserted into the commercial papaya cultivar, providing substantial virus resistance. Other approaches could provide disease resistance to transformed trees by inserting disease-resistance genes from resistant relatives (Gartland and Gartland 2004).

An application in the United States currently under research involves transferring resistance genes from the Chinese chestnut to the America chestnut, the population of which has almost been destroyed by an invasive Asian fungus. The characteristics of the genes makes transferring them by traditional breeding quite difficult, and genetic engineering offers a clear shortcut (Mann and Plummer 2002).

Fiber improvement. This category includes a host of potential GE transformations that would increase the amount of usable wood fiber or reduce its processing costs in pulp and paper making. Examples include GE products with reduced juvenile wood, reduced or more easily extractable lignin (see Hu et al. 1999), various fiber quality improvements and or quantity increases, and so forth. The advantages of this innovation are found after the tree is harvested and when the fiber is being processed.

Flowering control and sterility. Flowering control allows a delay of several years in flower initiation and, in the extreme, sterility. This control may be useful in preventing transgenic plants from transmitting genetically modified pollen to other plants, whether to adjacent nontransgenic plantations or into the wild forest. Because of functional redundancy, suppression of more than one floral regulatory gene is likely to be needed to achieve complete sterility. However, flowering control, including sterility or changes in the plant tree reproduction patterns, is fairly common in GE crops.

Whereas in agriculture, modifying reproduction may be undertaken to protect the developer's intellectual property, in forestry it appears to be more oriented to mitigating gene escape (see DiFazio et al. 1999; Strauss et al. 2004). The financial return to this innovation in forestry would come from the product's increased probability of deregulation, which is related in part to reducing public concerns with particular GE applications.

Investments That Shorten the Long Time Frames

Although the long life of trees creates a financial disadvantage in forestry, the time costs associated with long rotations need not be prohibitive. The tremendous expansion of industrial tree planting by the private sector in the last decades of the 20th century, for example, demonstrates that long-term investments in trees can have returns adequate to attract financial capital.

Moreover, investors need not await final harvest to experience a financial payoff from genetic engineering: some GE innovations could reduce costs early in the plantation growing cycle (Tables 5 and 6). For example, innovations that reduce establishment costs, such as weeding or pest control costs, will generate benefits early by substituting for expensive pesticides and reducing mortality. It is worth noting that the two transgenic trees currently commercialized—disease-resistant papaya and Bt poplar—both generate benefits early in the growing cycle. Similarly, herbicide tolerance, an innovation of considerable interest, also would generate financial benefits early in the growing cycle. The benefits to the tree grower would be captured in reduced weeding costs in the establishment phase, years one through three. Finally, although flowering control may not reduce early costs, it can be viewed as an enabling technology without which deregulation cannot be achieved.

Table 5. Timing of the Capture of Financial Returns of Interest in Forestry

Trait	*Early capture*	*Captured at harvest*
Herbicide tolerance	X	
Flowering control	X	
Fiber and lignin modification		X
Insect tolerance	X	
Disease tolerance	X	
Wood density		X
Growth		X
Stem straightness		X
Nutrient uptake		X
Cold, wet, drought tolerance	X ?	X ?

Table 6. Period of Benefit Capture

Innovation	*Financial benefit*	*Period of benefit capture*
Herbicide tolerance	Reduced weeding costs	Plantation establishment (1–3 years)
Bt gene	Reduced pesticide use	Early to mid cycle (1–10 years)
Fiber improvement	Reduced processing costs	Postharvest (10–40 years)
Sterility or changes in reproduction	Reduced gene flow	May be a condition of planting or improved product acceptance

Costs of Financing Tree Improvements: Some Country Considerations

Table 7 compares five categories of investment costs required for a transgenic tree in developed and developing countries. For two categories, the costs appear to be roughly comparable: development and distribution.[26] However, for deregulation, stigma, and time cost, the costs are likely to be substantially lower in developing countries. This finding suggests that the developing countries may have some comparative cost advantages in the commercialization of wood trees.

Table 7. Comparative Investment Costs

Investment	*Developed countries*	*Developing countries*
Development costs (stage 1)	Comparable	Comparable
Deregulation costs (stage 2)	High	Low
Distribution costs (stage 3)	Comparable	Comparable
Stigma costs (stage 3)	High	Low
Time costs (stage 4)	Generally higher	Generally lower

Development. A general assumption might be that more economically advanced countries would have an advantage in product development by virtue of their technical expertise and human capital—skilled workers with appropriate training. Although this may be true for some aspects of the basic science, it may not be true for applied research, where low-

[26] The separation between development and deregulation costs is somewhat arbitrary, since some development costs are incurred in order to ensure the product can overcome the regulatory hurdle.

cost but skilled technicians are needed.[27] Typically, the level of technical and research expertise is greater in developed countries. However, labor costs, even for technical people, are likely to be much less in developing countries. Furthermore, knowledge and technology are readily transferable across borders (spillovers). Therefore, although the basic technology may be developed in an industrial country, its application to a particular situation and environment may occur more readily in a less developed country, especially countries with high levels of certain technical skills. Table 7 therefore lists development costs as comparable.

Deregulation. Stage 2 deregulation costs are unique to transgenic plants; new products developed through conventional breeding are not regulated. The costs of deregulation may vary by country and depend on the nationality of the developer. In the United States, it has been estimated that tree deregulation is likely to make up at least 50 percent of the costs of the initial transgenic development and could be higher (Hinchee 2003). Pray (2005) found that for transgenic crops in India, the deregulation costs were much higher for the foreign firm than for a domestic Indian development firm or a multinational with an Indian partner. Also, deregulation costs are likely to be substantially lower if the transgenic has already been deregulated elsewhere.

Distribution. One might expect that the developed countries' more efficient transport, information, and general distribution systems give them an advantage of low distribution costs. Some evidence for this might be found in the quick and efficient distribution of transgenic crops in North America and other developed regions. However, distribution costs for transgenics are treated in Table 7 as roughly comparable between developed and developing countries.

Stigma. Despite the stigma associated with transgenic crops in some regions, the financial returns have been adequate to generate a host of new, transgenic agricultural products. These have been readily accepted despite the somewhat higher cost of seed and opposition in some consumer markets in many countries. For example, the area planted to GE agricultural crops increased from 2.8 million to 67.7 million ha between 1996 and 2003, and such crops were being raised commercially in 18 countries (FAO 2004b).

[27] For example, recent Vietnamese scientists have develop a new disease resistant tomato plant that can grow during the rainy season and withstand the lethal bacterium Raistonia solanacearum. CropBiotech Net 2006)

GE food and feed crops may face opposition in the market, but this is unlikely for harvested or processed wood. Although the planting of transgenic trees may be viewed negatively in some societies, it is unlikely that there will be a serious stigma attached to the wood itself, and even less to products made from that transgenic wood. Nevertheless, the developer may be required to make substantial investments to induce growers to adopt transgenic trees. These investments are likely to be more modest in developing economies, where the stigma of transgenics is typically smaller.

Time. Because many developing countries are in tropical and subtropical regions, a distinct financial advantage exists for nontransgenic tree investments. Trees often grow more quickly in these areas, resulting in a shorter harvest rotation. This has accounted, in part, for the large level of tree plantation investments that has occurred to date in these regions. It would be expected that short rotations would provide time cost financial advantages to transgenic tree innovations, particularly those that were captured only upon harvest.

Summary of costs. Although developed countries have some advantages in developing GE tree products, particularly at the basic research level, this advantage probably disappears or may be reversed for applied product development. Distribution costs appear to be similar in both developed and developing countries. Overall, there appear to be substantial advantages to investments in transgenic tree activities in developing countries, where deregulation may cost less, stigma costs may be smaller, and time costs are lower because of faster growth rates.

Product Pricing and the Distribution of Financial Returns

Product pricing. The developer of transgenic trees bears the initial development costs, the requisite deregulation costs, and the subsequent distribution costs. The developer must price the product to cover the marginal costs of production and distribution *and* also recover and receive a return on the fixed investment and deregulation costs. Thus the basic strategy is to charge a price high enough to cover marginal costs and some of the fixed costs yet low enough to induce widespread use of the innovative product. A price too high will discourage adoption. A price too low will not recover a sufficient portion of development costs.[28] One estimate for New Zealand forest growers is that they can afford to pay up to $2.00 NZ per stem of planting

[28] The developer will also have an interest in providing information and promoting the product. This may include information to try to offset the stigma attitude among final consumers, which might otherwise lead growers would not purchase the innovation.

stock, compared with $0.45 a plant for the best available crosses and up to $1.10 a plant for tested clones (Casasempere 2004).[29]

Transgenic trees comprise various inputs, however. One seedling may embody the characteristics of a superior tree, the result of traditional breeding, plus the clonal technology necessary for mass low-cost reproduction, in addition to one or more genes that were inserted through GE techniques. Each of these inputs represents an investment cost associated with its initial development. There is as well the cost associated with "assembling" the components into a single seedling. One approach would be to charge separately for the various attributes. Monsanto devised a system with transgenic canola seed whereby the farmer paid separately for the seed and the use of the embodied transgenic technology. In part, this appears to be an attempt to prevent farmers from using the seed obtained from the first planting for subsequent plantings, since Monsanto claimed intellectual property rights associated with the embodied technology. Another approach under discussion for some South American countries is to collect royalties for a crop at the millgate (Traxler 2005). However, such approaches may be less relevant for forestry, since the time periods between planting and flowering are considerable and the technology will probably become obsolete quickly. And for species that easily reproduce vegetatively, the "theft" of GE improvements could occur readily.

Although the time costs associated with tree growing appear to accrue to the grower, this interpretation is deceptive.[30] However, the time costs of growing affect consumer demand for the innovative product. If the time costs are prohibitively high compared with the price expected for the final product, the grower has no incentive to purchase the innovation and plant the tree. If the time cost to price ratio is high but not prohibitively so, the grower will be willing to pay only a modest price for the transgenic tree seedling. As the time costs continue to decline,[31] the grower will be willing to pay a higher premium for the innovation, thereby benefiting both the grower and the developer.

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[29] To be formally correct, estimates of this type require an assumption about the increased value of the output—for example, in increased volume.

[30] This question relates to the general issue in economics as to the price or tax "incidence." Specifically, what portion of the price (tax) must be borne by the producer and what portion can be passed on in higher prices to consumers?

[31] This same principle can apply to other costs also.

The revenue will be equal to the price times the quantity, where the maximum market depends on how much area is to be planted in the crop. The maximum price that could be charged is limited by the financial benefits that accrue to the user. In the case of a crop, for example, if an herbicide-tolerance gene saves $100 per ha in weeding costs, the developer could charge a maximum of $100 for seed sufficient to plant 1 ha. At a higher price, the farmer would ignore the innovation.[32] However, if the developer where to charge the full $100, the farmer would be indifferent to the innovation, and there would likely be few buyers. The literature suggests that transgenic crop developers typically price the innovation at about one-half the benefit to the farmer (Pray 2005; Demont and Tollens 2005).[33] Traxler (2005) notes that almost all the transgenic innovations that have been commercially successful have involved either herbicide tolerance or pest resistance. Traxler also observes that quality improvements in crops, such as protein-enhanced rice, have not yet been commercially successful, in part because of the reluctance of the market to pay more for the higher-quality, higher-cost product. By contrast, improved wood fiber that would reduce mill costs ought to be able to command a premium price, especially if planted on a large scale near a mill where the quality benefits can be captured through lower processing costs. Thus, the market possibilities for certain wood fiber improvements achieved through genetic engineering could be more positive than for some crop quality improvements.

Benefits: Some Issues

Economy-wide benefits from transgenics trees. The potential benefits to the economy from transgenic trees are found in the increased efficiency of production. The basic concept is that useful technologies allow the production of goods and services at lower financial (and resource utilization) cost and thus higher efficiency. The greater efficiency in one sector (wood products) allows resources to be deployed elsewhere without reducing wood outputs. Thus, the overall performance of the economy is enhanced, since more goods and services are produced with the same amount of resources.

[32] Although there are relatively few transgenic developers in many markets, these are likely to have limited market power, since they must compete with existing technology. Very high prices could be successful only where the innovation generated very high returns to the farmers.

[33] Demont and Tollens (2005) find the distribution of returns between farmer and developer in the range of two-thirds/one-third or three-fourths/one-fourth, with the larger portion going to the farmer.

On the producer side, the grower must decide whether to use the old product or adopt the innovative technology. As discussed above, this will depend upon the advantages of the new technology and the value of the innovation in the market. As noted above, both developer and grower share the benefits.

Finally, should the new, more efficient technologies become widespread, the general increase in wood production (compared with its level without the innovation) will put relative downward pressure on prices. As prices gradually decline, reflecting the productivity effects of the innovation, and future innovations appear that make even the earlier innovation obsolete, the developer and the grower will no longer be able to capture the price premium, which has all been passed through the market to the final consumer. Future price premiums will depend on the productivity provided by future innovative technologies.[34]

Who captures the financial benefits? A related question is how the financial benefits are distributed in societies with reasonably well functioning markets. The three principal players are the developer, the tree grower, and the processor/product consumer. The developer, the supplier of the product, has already incurred the product development investment costs and now must determine whether the financial benefits he can capture—the price and quantity in the market—will be adequate to cover the deregulation costs and return at least a portion of his investment costs. If so, he will proceed; otherwise he will not. If he continues to produce innovations that do not generate sufficient returns to cover the full investment costs, he will eventually go out of business.

To generate returns, the new product must be able to compete and offer advantages over existing technologies sufficiently large that it can take away some market share at a price that will provide the requisite returns to the developer. If the product is sufficiently superior—for example, if it lowers producer costs—it should be capable of generating a surplus that will accrue to the developer. Note that if the developer charges too high a price, his volume could be low and his revenues (price times quantity) could be small. The trick for the developer is to price in such a fashion that the grower can capture enough of the surplus to induce her to adopt the product even as the developer's share of the surplus is adequate to cover his marginal and

[34] In the near term, the benefits are captured and shared by the developer and producer; in the longer term, the benefits are passed to the ultimate consumer as price erodes.

fixed costs. The strategy, then, is to set a price that will maximize net revenues, even though this price will be below the maximum price that could be charged.

Nonfinancial benefits. Transgenic trees have the potential to create nonfinancial benefits as well. To the extent that they reduce chemical and pesticide use, environmental benefits are obtained. As noted earlier, transgenic trees may also play a useful role in bioremediation of harmful toxics in soils, and they can help restore species such as the American chestnut (Bailey 1997). Additionally, if transgenics can increase productivity and reduce wood production costs on tree plantations, they can promote a shift in commercial wood production away from natural forests to a crop mode. This has the great advantage of freeing society from dependence on large areas of the globe's natural forests for meeting industrial wood needs and allowing these forests to be designated for other purposes, including preservation in their natural state. Today, plantation forests account for more than one-third of the world's industrial wood; only 50 years ago, the supply from planted forests was negligible.

Transgenic Concerns

If the benefits of transgenic trees are as favorable as some of the discussion suggests, why is there so much opposition to their introduction? The concerns about transgenic trees are largely environmental (Mullin and Bertrand 1998), since they do not, in general, involve human ingestion. These include concerns that a transgenic tree may become invasive either directly or, through gene escape, indirectly—that is, a transferred gene might escape, perhaps via pollen, to a wild relative, increase the fitness of that relative, and enhance its ability to disrupt the existing ecosystem. While opinions on the risks of disruption due to gene escape vary,[35] this concern has prompted proposals for mitigating activities. Concern about gene escape is the major rationale for suggesting that only transgenic exotics with no close relatives in the region be planted—such as pine or eucalyptus in South America. The absence of close relatives precludes the passing of the gene (DiFazio et al. 1999). Other procedures designed to address these concerns include confinement, often used during field-testing, but more fundamentally flowering control or sterilization, again to preclude the inadvertent transfer of genes. Ultimately, regulators must determine the level of risk and the adequacy of procedures to address it.

[35] The U.S. National Academies of Science (2004) pointed out that for many crops, gene escape poses little hazard because the traits that make them useful to humans also reduce their fitness in noncontrolled environments (also see Snow 2003, Difazio et al. 2004). For a contrary view, see Lange (2004) and Williams (2004).

Commercialization and Location: Factors Providing Advantage

Even given the uncertainties—GE trees have the potential to generate substantial financial returns under many but not all conditions—many actors want to proceed. This section looks at factors that might provide a competitive advantage in certain countries. The assumption is that those interested in capturing the potential financial benefits will move toward locating their activities in countries providing advantages.

Much of the basic research necessary for the development of transgenic trees has already been undertaken and is part of shared knowledge in the scientific community. The techniques for applying biotechnology to trees are well known and being used in laboratories around the world. Most of the remaining challenges are associated with deregulation and public acceptance. The deregulation process requires that the product be judged safe not only from a health and safety perspective, but also environmentally and ecologically. Extra costs are likely to be incurred in engineering controls such as flowering modifications or sterility. Additionally, the public must be assured of the safety of the deployment of the transformed tree, and public education may be costly.

Given the above considerations, where and how might we expect deregulation to occur and transgenic trees to be commercialized in the future? Historically, a forest industry was based on the endowment of the forest resource provided by nature. Plantation forestry together with the growing globalization of the forest industry (Bowyer 2004) has irreversibly changed that model. Factors that appear to portend success in plantation and transgenic forestry commercialization include prior experience with plantation forests, tree improvement research, markets for the final wood product, tree type, ease of deregulation, and country sensitivity to GE products.

Experience and market situation. The organizations with the most direct interest in transgenic forest tree development, deregulation, and commercialization are likely to be countries and firms that have had substantial prior success with intensively managed plantation forestry. Australia, Brazil, Chile, China, New Zealand, South Africa, and the U.S. South all have had substantial experience with and expertise in intensively managed forest plantations; have large potential markets for innovative trees with substantial commercial potential; have generally low-cost, high-yield forests that make them strong competitors; and are in a position to exploit on a large scale their combination of experience, expertise, and large domestic markets.

Tree type. Another consideration is which species do particularly well in the various countries and are amenable to useful near-term transgenic innovations (Table 8). Any widespread transgenic program will require a tree species that can quickly replicated or "bulked up" from a few laboratory-developed transgenic trees to millions of low-cost seedlings. A problem with conifers has been the difficulty with replication. Techniques for pine clonal reproduction, such as somatic embryogenesis, have been mastered but remain costly and are not yet ready for widespread deployment. Thus, countries or regions that grow primarily conifers are likely to see a delay before the enabling technology, low-cost cloning, is adequately developed. Many deciduous trees, by contrast, are relatively easy to replicate through vegetative propagation. Because of the distinct technological and financial advantages in planting a tree that has low propagation cost, one might expect the first large-scale commercial applications of transgenic trees to involve a deciduous species that can be easily reproduced.

Table 8. Tree Types and Market Size

Country	*Tree type*	*Domestic market*
Australia	Coniferous and deciduous	Modest
Brazil	Coniferous and deciduous	Large
China	Deciduous	Large
Chile	Coniferous	Modest
New Zealand	Coniferous	Modest
South Africa	Coniferous	Modest
U.S. South	Coniferous	Large

Ease of deregulation. Although developing countries do not have a clear advantage in transgenic tree development, at least some may have a comparative advantage in deregulation.[36] As demonstrated in the study by Pray et al. (2004), a local developer or a multinational with a domestic partner appears to a have substantial advantage when it comes to achieving fast and low-cost deregulation. The optimum approach may be a joint venture between a biotech company in the developed world and partners in the developing world. The partners can then become the major agents in the deregulation process, and both parties share the proceeds from the revenues of the deregulated transgenic.

Where developing countries have the technical expertise for the applied stages of the transgenic innovation, the role of the developed country firm might be smaller or nonexistent. In China, for example, the role of the foreign firm in the development of the transgenic poplar appears negligible. However, some foreign scientists do appear to have played a role and most of the basic research was done elsewhere.

Country sensitivity to GE products. The stigma attached to GE products and, more generally, ecological concerns about gene escape could affect the ease and timing of deregulation. For example, concerns have been raised about the implications of gene escape from a transgenic indigenous species to the wild forest population (Williams 2004). Such concerns could delay the deregulation of transgenic loblolly pine in the United States but may have less effect on deregulation of transgenic pine or eucalyptus in Brazil, since there are no native forest trees of the same or related genera (DeFazio et al. 2004).

The global market for tree germplasm. In concept, trade in transgenics can involve two types of goods: the transgenic tree and its live germplasm, which is available for planting and reproduction, and the commodity wood and products made from it. Thus, there are two possible industries and two possible markets: that of the tree transgenic produce developer and that of the tree grower. Access to international markets is likely to be different for the two industries.

In general, under the Global Trade Agreement (GTA), an innovative commodity is not subject to international trading restrictions unless it is deemed a health or safety hazard, which

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[36] Some of the ease of deregulation may reflect the degree of acceptance within the country toward GE. For a number of harsh criticisms of GE generally, see www.social-ecology.org/article (accessed March 2006).

has often been the argument against transgenic crops.[37] For wood, however, the commodity would be either raw wood (logs) or wood products, such as lumber, pulp, or paper (Sedjo 2005). In neither case does it appear that a serious argument can be made for trade restrictions based on health, safety, or environmental damage, since the wood cells from the transgenic tree would be dead.[38] By contrast, the transgenic germplasm—the living modified (transgenic) plant or its live seed—can be regulated because of the general regulation most countries place on transgenic plants.[39]

Summary of factors providing an advantage. The above suggests that GE trees are most likely to become commercial first in countries that (1) already have large areas of well-functioning forest plantations and areas for expansion; (2) will have access to large markets, either domestic or abroad; and (3) have foreign markets unlikely to erect serious barriers to transgenic wood. The tree types most likely to be genetically engineered are deciduous, because of the high replication costs with conifer. The countries that establish large-scale commercial transgenic plantations are likely to have a friendly deregulation process and a population that is not hostile to genetic engineering and particularly transgenic trees. Finally, the ease of deregulation may depend on the extent of concerns about gene escape to wild forest populations. These concerns may be greater in developed countries where transgenics would be domestic species.

China and Brazil

Two countries, China and Brazil, appear to have most or all of the preconditions that would make them early deregulators and commercializers of transgenic trees (Table 9).

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[37] A Pew (2005, 15–16) report notes the conflicts within the European Union on allowing importation of transgenic crops, even when the EU Commission recommends lifting the bans to comply with new EU legislation.

[38] Despite international GTO agreements laying out biosafety criteria, guidelines, and conditions under which imports may or may not be banned, the importation of GE products continue to be banned despite meeting the EU biosafety criteria (see ISAAA 2005).

[39] However, the ability of a country to prohibit genetically modified crops may be limited. Recently, the European Union Court of First Instance ruled that Austria failed to present science-based data to justify banning the planting of genetically modified crops (CropBiotech Net 2005).

Table 9. China and Brazil: Preconditions for Early Adoption

	China	*Brazil*
Market size	Large	Large
Forest plantations	Abundant	Abundant
Deregulation costs	Modest	Likely modest
Easily propagated species	Poplar	Eucalyptus
Public acceptance	Widespread	Widespread
Current plantings of transgenic trees	Yes	No
Active tree breeding and GE research	Yes	Yes

For decades, China has been establishing very large areas of traditional tree plantations for both protection and commercial industrial wood production (Xu et al. 2004).[40] China has both large domestic markets for industrial wood and also large forestland rehabilitation and protection efforts under way. Research into GE forest trees was begun in China in the late 1980s by the Research Institute of Forestry, Chinese Academy of Forestry. A total of 54 GE trees were created (Wang 2004). Limited amounts of transgenic poplars with a Bt gene to resist insects have since been planted. China now appears closest to widespread deployment of a GE poplar, a tree that could provide for substantial land rehabilitation and whose genome has been well studied. The tree is also very easy to propagate vegetatively. The only precondition that China does not meet is that the transformed poplar gene could be transferred fairly readily to the wild poplar population.[41]

Although its situation is different in many respects, Brazil also meets almost all the preconditions for transgenic trees. Brazil has large areas of plantation forest and has become a major world supplier of certain types of forest products, especially pulp. Although the tree types in these plantations vary, large areas are in eucalyptus, which has been greatly improved through traditional breeding. It is the eucalyptus that is likely to be the first transgenic forest tree commercialized in Brazil.

[40] According to FAO(2005), China has experienced substantial reforestation in recent decades due to large-scale plantation establishment.

[41]However, this could be viewed positively as this might confer pest resistance upon much of the wild tree population that has been under severe insect stress.

Like China, Brazil has been actively involved in research on forest trees, with a focus on eucalyptus (Chaix and Monteuuis 2004). One research project reported as currently under way involves developing a transgenic eucalyptus that would produce about 30 percent to 40 percent more wood fiber.[42] Although Brazil only recently began to allow transgenic crops, the acceptance of transgenics appears to be high. Domestic concerns about transgenics appear to be minor, and since eucalyptus is an exotic in Brazil, gene escape poses little threat to native forests.

A likely scenario is that the transgenic eucalyptus will be deregulated and commercially planted in Brazil within the next several years. If the productivity gains are anywhere near as good as anticipated, the increases in industrial wood production from Brazil over the next decades could be substantial as the productivity on newly planted sites increases while the area of tree plantations continues to expand.

The United States and Elsewhere

In general, one would expect to see transgenic trees readily adopted where the net benefits would be greatest, and fewer adoptions—and perhaps active opposition—where net benefits are modest or nonexistent.

In Europe, unlike China, Brazil, and perhaps parts of the tropics, the economic gains associated with transgenic trees are likely to be quite modest, primarily because of the longer growth periods to maturity. From a narrow economic self-interest perspective, it is unlikely that the EU would be very receptive to the importation of transgenic tree germplasm for establishing forests, since it has little to gain.[43] Furthermore, the overall view of EU countries to transgenics plants is generally negative.[44]

The situation in the United States is quite different. The United States has led the world in the development of transgenic technology in agricultural crops (Clive 2004) and now in trees. Most of today's GE agricultural crops were developed in the United States, and the largest areas of transgenetic crop plantings have been there. Also, a recent study estimates that roughly one-

[42] Personal conversation, Sharmane MacRae, Quebec City, Canada, September 27, 2003.

[43] However, to the extent that other regions adopt economically efficient transgenic commercial operations, Europe's competitive position in industrial wood product deteriorates.

[44] See Tothova and Oehmke (2005) for a analysis of conditions that may lead to different standards rather than the harmonization of standards.

half of worldwide research on genetic modification generally and nearly one-half of the reported worldwide research in tree genetic modification are taking place in the United States (Chaix and Monteuuis 2004).[45] Furthermore, a study by Walter and Killerby (2004) estimates that almost two-thirds of the worldwide field trials of GE trees have been undertaken in the United States.[46]

Although the United States has been a leader in the development, deregulation, deployment, and commercialization of transgenic crops, deregulation of a transgenic forest tree may be some time off. The deregulation of the transgenic papaya may be more an exception than a sign of the future. U.S. forests have relatively modest yields and long rotations, and therefore the financial advantages of transgenics may be modest at best. Even the South, which enjoys relatively high yields and short rotations, is not as favorable to tree growth as parts of the tropics and subtropics. All U.S. regions face the high costs and lengthy process of deregulation and public opposition associated with transgenic trees. In addition, for the United States, technical problems exist. Transgenic tree research in the United States is oriented toward two plantation tree types—conifers, particularly pines, and poplar. As noted earlier, transgenic pine cannot yet be mass-produced. Although progress is being made, further work is needed to develop low-cost applications.

In addition, widespread wild pine stands raise concerns about gene escape from transgenic plantation trees (Williams 2004). Strauss (in Mann and Plummer 2002), a well-known tree researcher at Oregon State University, believes that the industry will not be able to grow transgenic trees in plantations until the risks of gene escape are minimized. Although these issues may eventually be adequately addressed, substantial laboratory research and field trials will almost surely be required before deregulation and commercialization are achieved.

Because of the relatively high costs of deregulation and deployment of transgenic trees in the United States, tree improvements developed there may be deregulated and deployed abroad. The opportunities look most promising in South America and southern Africa, and

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[45] Chaix and Monteuuis (2004, 48) note, "In Europe forestry research priorities now focus on stronger synergies between biotechnology and conventional selection and breeding programmes for wood improvement." Tree improvement tends to involve genomic and proteomic approaches to access selection traits rapidly by taking advantage of advances in modern plants.

[46] Walter and Killerby (2004) indicate the United States has field-tested 103 forest trees, China 9, the countries of Europe a combined total of 23, and the rest of the world, 22.

perhaps tropical Asia. Indeed, it may be that the first applications of the deregulated transgenic pine will occur in countries without native pines— tropical regions in the southern hemisphere, such as South America or New Zealand.[47]

Possible Scenarios

Although there are substantial concerns about the release of deregulated GE trees (see Campbell and Asante 2001), the fact remains that transgenic trees have already been released, and more trees are likely to be deregulated and commercially deployed in the not-too-distant future. In general, we have argued that in the most likely scenario, GE trees would be commercialized in countries that expect the largest economic gains from the adoption of the technology. Conversely, countries that foresee only modest gains from transgenic trees are unlikely to proceed with either rapid or widespread adoption. Where the gains are substantial, the regulators might also be more accommodating. If the gains are modest, particularly where the new technology would compete with existing industries and face local hostility, regulation could well be more stringent. Thus, as in agriculture, we might expect some regions to commercialize transgenic trees, and others to adopt them sparingly or prohibit their planting altogether.

As suggested above, the most likely countries involved initially in GE tree commercialization appear to be China and Brazil. No country has more land in planted forests than China and there are both environmental and economic benefits to China from its rehabilitation and production forests. China's GE research, development, and commercial applications have been stimulated primarily by the state with strong ecological and protective purposes in mind. China has planted large areas in poplar and pine as well as exotic species. In western China a "Great Green Wall" of forest is being established to help control desertification. It is difficult to imagine China not making use of transgenic trees that offer serious advantages, even given some international opposition. Once a transgenic poplar with insect resistance is proven successful, the incremental costs are likely to be negligible, and expensive and often environmentally harmful pesticide applications can be reduced. Given the large demands of the Chinese economy for industrial wood, there is little reason to expect that other transgenic trees will not also be introduced to enhance industrial wood production and wood properties.

[47] A possible issue here relates to ownership of intellectual property associated with the transgenic and particularly with capturing the rents associated with that property in the context of a foreign country.

Brazil, by contrast, is likely to look toward transgenic trees almost exclusively to enhance its already formidable advantage in certain types of industrial wood production, particularly pulpwood. Research and development in Brazil comes largely from the private sector and has a strong industrial orientation. Although the expansion of Brazil's domestic market may eventually draw a large portion of its production out of the international market, this has yet to occur. Indeed, given the high yields and the large areas of land suitable for plantations, there is no physical reason why Brazil could not continue to produce large and growing volumes of industrial wood for both markets, domestic and international. However, given the time required for planting and growing large areas of transgenics, we would agree with Seppala (2003) that it is difficult to foresee significant impacts on timber and the forest products industry until after 2020.

The ecological implications of transgenic trees are likely to be of greater concern in China than in Brazil. The eucalyptus is not native to Brazil, and therefore gene escape is unlikely to affect native species anywhere in the western hemisphere. Additionally, a eucalyptus with greater fiber content will almost surely not give a transformed wild tree additional "fitness" and turn it into an invasive plant.[48] The ecological implications of planting transgenic pine would be similarly small, given the absence of indigenous pine. Thus, ecological objections in Brazil are likely to be weak. A longer-term issue may be land-use change. For example, if increased specialization in industrial wood production occurs in a few very productive regions—the tropics and subtropics—absent innovations that allow for very high growth and yields in temperate and/or boreal regions, what are the implications for the future of these forests?

An important aspect of the emerging forest products industry is the extent to which transgenic wood (as opposed to germplasm) is internationally tradable. Under the current WTO rules, nonliving transgenic wood, whether raw logs or wood products, cannot be restricted in international trade simply because it is transgenic. Under this arrangement, there is little reason not to expect production to move to low-cost regions. However, as we have seen numerous times, the rules of the WTO are often challenged for reasons that could be viewed as protectionist.

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[48] See Snow (2003) for a discussion of genetic "fitness."

Conclusions

This report finds that the economic viability of transgenic trees has not yet been adequately demonstrated in the market; nevertheless, under many conditions transgenic trees are economically viable. The report anticipates widespread adoption of transgenic trees, but probably not before the next decade or two. The principal barriers to widespread adoption are deregulation and the stigma associated with transgenics in some markets. Although some countries may prohibit transgenic trees indefinitely, it appears very unlikely that such a prohibition would be universal, particularly given that China has already undertaken limited deployment of transgenic hybrid poplar. Also, the forest product industries of other countries see much promise in the introduction and production of transgenic wood.

The deployment of transgenic trees may first be accomplished in a major way in countries where the potential benefits could be large; China and Brazil appear to be attractive candidates. Over the longer period, other countries are almost sure to participate. The inherent advantages that have made certain regions successful locations for forest plantations, together with a willingness to adopt the new technology, will be important in determining which countries are the first to commercialize and deploy transgenic trees. The economics of transgenic trees tend to be favorable where yields are high and rotations short. Thus, countries that already have demonstrated success with fast-growing forest plantations are likely to gain an additional economic advantage from GE trees.

Today, forest resources and the forest industry are being profoundly affected by the large-scale transition from harvesting natural forests to growing plantation trees as a crop. Globalization is facilitating this transition, as new tree plantations are being established in the regions with the greatest comparative advantage. International trade has allowed goods produced in one region to be transported and traded in another; globalization now extends this model to factors of production, including physical and financial capital. The continuation of the globalization phenomenon provides a prime opportunity for the introduction of transgenic trees in regions with the greatest potential and least opposition.

Although important technology has been developed primarily in the industrialized countries, the better utilization sites are likely to be found elsewhere—largely in the tropics and southern hemisphere—and developed perhaps through joint technology contracts. Additionally, much of the basic research necessary for the development of transgenic trees has already been completed and is part of shared knowledge in the scientific community. The techniques for applying genetic engineering to trees are well known and, in fact, being used in laboratories and field tests around the world. Many of the remaining challenges to commercialization and deployment are associated with deregulation and public acceptance.

Transgenic trees are not likely to be equally profitable everywhere. Many countries have few incentives to introduce transgenic trees and indeed may have economic reasons to oppose them if there are few direct benefits. The polarization in acceptance of transgenic trees could, paradoxically, facilitate increased globalization of the world's wood production. A dichotomy in the use of transgenics could further increase the comparative advantage of the adopters over the nonadopters. Indeed, in today's world the continued relocation of the forest industry will likely place additional competitive pressures on the forest products sectors of traditional wood-producing countries, even without the introduction of transgenics.

In summary, transgenic trees are likely to become commercialized in major regions of the world for both control of pests and to enhance wood quality production. Some regions, mostly in the tropics and subtropics, will increasingly specialize in wood and paper production, using transgenics where appropriate and exporting products to the rest of the world. Other regions of the world will resist transgenic trees, in part because the direct returns will likely be small.

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