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The year 2004 marked the anniversary of two very different but revolutionary discoveries. The 50th anniversary of the discovery of the structure of DNA by Watson and Crick, the building block of all life on earth, and the 100th anniversary of the positive identification of chestnut blight at the New York Botanical Gardens. Both of these events had an enormous impact on the future of our forests. Today, sequencing of tree genomes such as the Populus genome project, provide a foundation of information from which discoveries in growth, disease and stress resistance, wood characteristics and plant interactions can take place. These innovations may provide the opportunity to restore threatened tree species, meet the increasing demand for wood and wood products, and preserve native forests, but balance must be given to addressing arising issues to ensure societal, ecological and economic benefits.

The Institute of Forest Biotechnology works for societal, ecological and economic benefits from appropriate uses of biotechnology in forestry worldwide. It is a unique organization that brings together diverse sectors and stakeholders to address the opportunities for native forest protection, restoration of threatened tree species, scientific advancement, and consideration to societal and cultural issues at the forefront of a developing technology.

The goals of the Institute are being practically met by its Four Cornerstone Programs.

- **Heritage Trees®**. This program seeks to conserve trees that have special significance for cultural, ecological or historic reasons in landscapes around the world. It promotes and integrates the application of emerging biotechnology, along with traditional approaches, to rescue threatened species or ameliorate threats to individual trees of special significance.

- **Ecological Ramifications**. This program addresses the concerns that exist regarding ecological disturbances from use of genetically modified organisms (GMOs). This will be accomplished through symposia and projects, and partnering with biotechnologists and ecologists to fill the knowledge gaps.

- **Societal Issues**. Because trees hold cherished places in our culture and heritage, efforts will be made to identify the social, cultural and ethical issues at stake in the application of biotechnology to trees, and to address those concerns through forums and research reports to help guide the public debate.

- **Outreach**. This program focuses on communicating the fundamental science and the risks and benefits to society, the environment and the economy.

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Executive Summary

The conference, New Century, New Trees: Biotechnology as a Tool for Forestry in North America brought together 80 participants for a two-day forum held November 16 – 17, 2004, Research Triangle Park, North Carolina. It focused on several questions:

- What is the history of forest biotechnology?
- What is the status of forest biotechnology research and development in North America?
- What are the projected future products and their respective net benefits?
- What are the key scientific issues?
- What are the key societal and public policy issues for forest biotechnology in North America?
- What are appropriate strategies for the future?

The impetus for forest biotechnology has been driven by many factors. Our natural ecosystems are subject to increasing pressures, and negative effects can already be seen in some regions of the world. In the years 1999 – 2000, 9.4 million hectares of forests were lost worldwide (FAO 2001). Tropical deforestation accounts for 20 percent of the world’s greenhouse gas emissions and the loss of essential terrestrial and freshwater resources for humanity and critical habitats for endangered species.

There is significant social and ecological value in conserving larger areas of biodiversity-rich natural forests and in reducing economic demands on those forests by increasing yields from planted forests. This suggests that total value in plantations is not simply a financial equation. While intensive forestry and biotechnology are not panaceas in the absence of concerted efforts by governments and the private sector to expand protected areas, they are important tools that support sustainable forestry programs.

The Science

The 20th Century was the century of chemistry, physics and microelectronics. The 21st Century may become the century of genomics, and forest tree genomics is moving at a remarkable rate. Progress is particularly impressive when considering the exceptionally large genome sizes of some trees of interest. For instance, the genome of *Picea glauca*, a species of major economic importance in Canada, is almost 10 times larger than the human genome. Although obtaining the complete genome sequence of any conifer is impractical with current technology, it is already possible to access sequences of genes expressed in a particular tissue at a given time. Sequencing and bioinformatics technologies are advancing rapidly and planning for a major pine genome initiative is underway.

The first draft sequence of the hybrid poplar genome is nearing completion and with this, new research opportunities will appear. The discovery of genes for enhanced carbon storage and enzymes important to ethanol conversion using the pedigreed populations of conventional improvement programs will help to commercialize poplar for carbon and energy markets. Once the gene catalog for poplars and certain conifers nears completion, it will be possible to transfer the knowledge gained to other less economically important species or to species given priority by developing countries. Population genomics will allow us efficient access to the huge reservoir of natural genetic variation in forests that previously was not readily available for use in tree breeding. One of the greatest gaps lies in integrating genomic technologies with processes that scientists and managers value. More specialized approaches to forest management can result in significant increases in both biodiversity conservation and sustainable wood production.
A great deal of basic work is occurring in places that are not normally viewed as forestry centers, such as the Plant Genomics Consortium, located at the NY Botanical Garden International Plant Science Center. Here work is being done on comparative plant genomics that integrates Botanical Garden research expertise in plant systematics and economic botany with cutting-edge genomic techniques to break new ground in molecular biodiversity and genome evolution.

In general, scientists will use forest tree genomics to focus on several important areas of investigation: 1) pest and pathogen resistance, 2) desired silvicultural characteristics, 3) flowering control, and 4) regulation of the physical and chemical properties of wood.

The Economics

Even with predicted stagnant real prices for wood and wood fiber over the next two decades, there remain compelling trends that strongly suggest that forest biotechnology will be economically important in the long term. These trends include continued population growth, the rapid industrialization of China, India and other developing countries, and a finite supply of land suitable for forest plantations.

Timberland investment as an activity distinct from the forest products industry now amounts to about $24 billion and is growing at about 20 percent per year. Financial pressures on integrated forest products companies, market conditions, and tax policies are driving separation of the tree-growing functions from the wood processing and marketing functions. Information flows that once took place within a single firm are now relegated to market-based transactions. Obtaining the apparent social benefits and private gains from forest biotechnology requires new ways of organizing information flow. Possible solutions include the pricing of R&D into such “technology products” as clonal regeneration material, enhancing forestry-based venture capital, and developing long-term growing contracts between timberland owners and manufacturing companies.

The forestry market is one of the last global agronomic systems not predicated on elite germplasm. The value proposition for forest biotechnology exists principally within two product areas: germplasm and transgenic traits. A crucial first step in full commercialization of these technologies will be vertical communication about value capture and allocation through the industry.

The Regulations

USDA APHIS recently announced a plan to do a programmatic Environmental Impact Statement in anticipation of changes in the regulations for field-testing and deregulation of transgenic plants. The goals for the regulations are to have science-based triggers that are rigorous, consistent, and easily understood; to be effective, flexible, and dynamic; to impose a degree of oversight proportionate to the potential risks; and to meet both domestic and international needs.

Trees differ from annual crops in that they are long-lived, undomesticated and seed dormancy is common. To address these issues and their potential environmental impacts, modification of floral development and mitigation of the risk of transgene spread will need to be considered on a case-by-case basis, depending on the gene and potential impacts. Because of functional redundancy, suppression of more than one floral regulatory gene may be needed to achieve complete sterility. There may be cases where sterility is not desirable, such as for the restoration of Heritage Trees® where reproduction is necessary to achieve the ecological benefits of reintroducing a valuable tree species and restoring an ecosystem.
The Issues
Public perceptions of biotechnology in North America are cautiously favorable, with the greatest support for medical and environmental applications (2004 Poll in US and Canada). It should be noted that the primary concerns with environmental products is the long-term risk to the environment. These two views should be considered in concert with each other. There is a hierarchy of perceived benefits and risks that is reflected in what is being modified and the purpose of the modification; modification to micro-organisms and plants are of less concern than modifications to animals and humans. The factors most predictive of a person’s position on GE foods are related to the specific attributes of the genetically engineered trait/product: utility, risk and moral acceptability. Confidence in the regulatory system is an important factor in determining how positively biotechnology is viewed. Based on the experience of agricultural biotechnology, it will be important to explore the parameters associated with a social license for commercializing transgenic trees. There is potential for a convergence of interests among the business world, conservationists, local communities and the world’s consumers. How can forest biotechnology be harnessed to contribute to environmental and biodiversity concerns while meeting society’s need for forest products? While great progress is being made in developing the scientific capacity to implement biotechnology in North America, we are lagging behind in the science required to address the ecological and social issues surrounding the technology of genetic engineering. There is a real need to begin ecological studies of large field trials, including marker genes and model systems.

The Future
Genomics and biotechnology are invigorating traditional genetics programs in forestry and agriculture. The genomics phase is largely data collection. The “post-genomics” phase moves past data generation to utilizing the information in testing functions of individual genes and hypothesis driven research. Systems biology combines all of the “-omics” and serves as a platform for translating new information across many disciplines and enabling people doing field and laboratory research to come together to answer problems using common data sets. Forest biosciences are in a unique position to benefit from and contribute to advances in biotechnology and systems biology. Forestry is a multi-disciplinary endeavor that urgently needs new technologies and approaches to meeting complex challenges such as ecosystem restoration and sustainable production of renewable energy and materials. Forestry needs to incorporate biotechnology so that it can add value and useful new perspectives. Greater public investment in the genomics of tree species is a timely and essential step toward integration of the forestry and biotechnology communities. The international Poplar Genome program has demonstrated the feasibility and value of tree genomics. The critical next step is to tackle the large and complex genomes of gymnosperms. Loblolly pine was identified as the model species for gymnosperms because of its extensive database from controlled breeding programs and biotechnology research. The loblolly pine genome project is exciting and offers tremendous potential. The Institute of Forest Biotechnology commits to convening the community that would define and analyze the ethical, legal and societal implications (ELSI) of such a project. IFB will continue to work to meet the ELSI challenges that have been presented at this conference.
Conclusion
The purpose of this conference was to examine the status of and opportunities for application and use of forest biotechnology in North America, including identification of target areas for research, and the societal and regulatory issues to be resolved. The knowledge framework developed to date in biotechnology and forest genetics is impressive and represents a remarkable record of accomplishment in a short time.

The potential long-term ecological benefits and economic opportunities associated with forest biotechnology are compelling but should be considered on a case-by-case assessment of trait/product combinations to ensure mitigation of environmental impacts. Realizing these benefits and opportunities will require substantial investments over several decades in both the public and private sectors. Near-term successes in both basic research and commercial applications will play critical roles in attracting investment.

Public support and understanding are essential to the long-term success of forest biotechnology. Efforts to address societal and ecological aspects of forest biotechnology have been inadequate. Strengthening these efforts is essential to shaping effective regulatory approaches and to sustaining necessary investments.
NEW CENTURY, NEW TREES
Biotechnology as a Tool for Forestry in North America

Overview of Forest Biotechnology in North America
Overview of Forest Biotechnology in North America And Major Challenges Facing Realization of This Potential

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Abstract

The term Forest Biotechnology is broadly used to include two distinct but complementary technologies. Genomics and molecular biology are fields of pure scientific endeavor where enormous progress is yielding fascinating new knowledge about plant functions, and this knowledge of itself is not viewed by the public as threatening. In contrast, genetic engineering is viewed as the creation of modified plants for commercial deployment in clonal systems with associated risks to ecosystems. Most such modifications that have been publicly discussed are viewed by the public as benefiting tree growers and forest products manufacturers while the public and ecosystems are potentially exposed to unknown risks. Opinion research and dialogues in Canada and the United States reveal the public is willing to accept risks when there are clear personal benefits but not when there are only personal or societal risks. The world market for biotechnology products of all kinds is on the magnitude of $58 billion. So far, the limited commercial potentials for forest biotechnology applications that are being discussed are limiting, the time lines for development and testing are very long, and market values are miniscule in comparison to medical, agricultural and food products. There are large strategic issues about deployment in the United States where most forest land is owned by individuals, and companies produce only a relatively small portion of the wood they consume. Far more imagination and innovation are needed to define a way for the technology to pay off with trees and forests. Increased discussion of the potential for genetic engineering to impart resistance to a wide array of tree diseases is beginning to reveal societal benefits the public can understand. During the last year there have been many policy developments in the United States, Europe, Africa and elsewhere that indicate wider general acceptance of genetically modified agricultural crops. Use of genetically modified trees means growing use of clonal plantations in “domesticated” forests, while the public and conservation organizations view forests as wild and natural systems. Progress is being made in accepting the notion that the world’s wood needs can be produced in intensively managed forests that represent less than a fifth of the total forest area, but much more dialogue is needed to broaden acceptance and define how and where such forests would be sited and managed.
**Introduction**

It is perhaps useful to think about forest biotechnology in two distinct dimensions:

- The first dimension is the pure science of molecular biology and genomics and the use of knowledge to further our understanding of the evolution and function of plants in general.
- The other dimension is the genetic engineering of plants and the development of plant cloning systems to create and deploy trees into planted forests of commercial value.

Those two dimensions are clearly complementary, but they are distinctly different in their goals and how the public reacts to them. Much of the public debate and press coverage is about the latter dimension, and the first, purely scientific, dimension is often overlooked by those who see forest biotechnology only in terms of market products and values.

One thing they share in common is a very long time horizon to make meaningful progress. My own involvement with forest biotechnology goes back about 20 years, and the first potentially commercial products from forest biotechnology are still in the very early testing stages. That’s a very long time for commercial development in a world where the time value of money causes most investors to view initiatives as irrelevant if they extend beyond six or seven years!

Within the context of genomics and pure molecular biology the advances in forest biotechnology have been enormous by any measure! Scientists are using forest biotechnology every day to expand their knowledge rapidly about how genes work in plants and how plants function in ecosystems.

The foundation sequencing of the genome of *Arabidopsis* generated new techniques as well as basic knowledge of genes that fueled a renaissance in the way we look at trees. Sequencing of all or parts of the genomes of several tree species is in various stages of completion. There is the loblolly pine genome project in the United States and work that Ron Sederoff and others are doing with pine. The *Populus* genome sequencing project based at the Oak Ridge National Laboratory in September announced release of the basally annotated 480 Mb *Populus* genome to the public through the Joint Genome Institute (JGI). ArborGen LLC, through its partner, Genesis, in New Zealand, has sequenced the active genes of *Pinus radiata* and *Eucalyptus grandis*. A consortium in Brazil headed by Dr. Dario Grattapaglia is also working to sequence the active genes in *Eucalyptus grandis*. Many other organizations are working to sequence specific segments of the genomes of these and other tree species.

As a result of the sequencing of these tree genomes and active tree genes, as well as earlier genome sequencing in *Arabidopsis*, tobacco, maize and other agricultural plants, there is an enormous body of genomic information to fuel massive future discoveries about how plants grow and form tissues, how they repel competition from pests and how they relate phylogenetically to other flora and fauna in their ecosystems and biospheres.

A lot of basic work is occurring in places that are not normally viewed as “forestry” centers. As one example, consider the Lewis B. and Dorothy Cullman Program for Molecular
Systematics Studies that began in 1994 at The New York Botanical Garden. Most of their work focuses on phylogenetic studies of plants and fungi and relates to plant classification, historical biogeography, plant-animal interactions and character evolution.

Scientists at The Garden are using genomics to gain new knowledge about the evolutionary origins of the seed and flower with a focus on gymnosperms, especially cycads — members of an ancient family of tropical gymnosperms that are similar to palms. They have generated DNA sequences for several genes known to be involved with development of seeds and flowers in higher plants.

The Plant Genomics Consortium includes The New York Botanical Garden, Cold Spring Harbor Laboratory, New York University and the American Museum of Natural History. Its work focuses on comparative plant genomics that integrates Botanical Garden research expertise in plant systematics and economic botany with cutting-edge genomic techniques to break new ground in molecular biodiversity and genome evolution.

Whenever world class scientists in first class institutions are working on molecular characteristics of trees they are learning things that will advance forest biotechnology.

I am sure that there are many more excellent examples of ways in which the science of forest biotechnology is being used aggressively with innovation to increase our knowledge of plants and animals. The concepts of forest sustainability have progressed from the original forestry principle of “sustained yield” of crops to the larger concept of sustained ecosystems in all of their biodiversity dimensions. Much of what we need to know to achieve that kind of sustainability depends on knowledge that can only be obtained at the very basic scientific level.

Even though the Sierra Club opposes the genetic engineering of trees it sees a potential for the use of biotechnology at this level. In its Position on Genetically Engineered Trees that it presented to APHIS last year it noted, “If genetic technologies are applied to silviculture, it should be to study and identify existing diversity. If trees are to be bred like agricultural crops, then genetic sequence data and polymorphisms should be used to steer selective breeding and accelerate identification of the desired combinations.” This reflects the views of many scientists that many of the greatest practical opportunities for forest biotechnology — especially in the nearer term — may be through refinement of classical tree breeding strategies through earlier screening of candidates and the presence or absence of desired traits. That would clearly expedite gains from tree breeding with much greater efficiency.

This facet of forest biotechnology is pure science at the molecular level that leads to new discoveries that are important to scientists. At the same time they are as fascinating to the public as Michael Fay’s breathtaking transect across equatorial Africa or the photographs beamed down from the Hubble telescope or from the probes on Mars. It poses no risks and the knowledge itself has intrinsic value.

That picture changes dramatically when we shift focus to the other dimension of forest biotechnology — the commercial dimension based on genetic engineering.

Genetic engineering of trees introduces the question of economic value: how much value and for whom — business or society? It’s the dimension that raises the parallel question of risk: how much risk and to whom or what — business, society or ecosystems? This involves large commercial investments with long time lines to realize a payback. It involves regulation and
testing and marketing of new products, and that often involves great difficulty in quantifying a market value far into the future.

It involves natural public concern about any new technology that is so complex the public cannot possibly understand it. This is where everyone seems to struggle to define economic value and biological risk in ways that are acceptable to society.

Let’s think about this in contrast to medical and agricultural biotechnology where there is considerable public awareness and where progress is being made in gaining acceptance of the technology and its products.

A 2002 presentation by Dr. Morokot Tanticharoen, Director of the National Center for Genetic Engineering and Biotechnology in Thailand, estimated the total world market for biotechnology products at $58 billion. His data suggested that about $15 billion of that market is in pharmaceuticals, $14 billion is in agriculture and $20 billion is in food. He noted that malaria affects 200 to 400 million people and kills 1.5 to 2.7 million children annually. Tuberculosis infects 120,000 people in Thailand alone. Over 1.2 million cases of dengue hemorrhagic fever were reported to the World Health Organization in 1998. Biotechnology offers potential solutions to those diseases.

An on-line document at the University of Limerick in Ireland states that proteins of therapeutic value produced by recombinant DNA technology now account for about a fourth of all new drugs coming on the market and products thus far approved represent an annual global market value of around €30 billion.

Such basic numbers make our first challenge in commercial forest biotechnology very clear: medical and agricultural biotechnology commercialization is occurring in global markets that are measured in billions of dollars of annual market value for products that apply to tens to hundreds of millions of patients or consumers. In contrast, most analyses related to the value of market enhancements for forest plantations range in size from tens to perhaps at best a few hundred million dollars — not billions of dollars — annually. Yet, the timeframes to develop and test forest products are often even longer and the meter on the time value of money ticks relentlessly.

Most of the economic value of world forestry is related to commodity products like pulp and mainstream paper grades and lumber. Most of them come from forests that grow over many years in somewhat natural settings, in contrast to commercial agriculture that all results from intensive farming annual crops under controlled conditions. Over time, however, an ever-rising portion of industrial wood products are coming from plantations and that will tend to augment market values. There are significant public social and intrinsic ecological values in preserving larger areas of richly biodiverse natural forests as a result of greater yields from planted forests. That suggests that total value is not simply a financial equation.

Modified lignin is the one product value that is cited most often in forestry and it is instructive about this whole forestry challenge.

Lignin is the organic polymer in wood that binds the cellulose fibers together. In wood pulping, the chemical digesters dissolve the lignin from the fibers so the two elements can be separated. Although a few companies like MeadWestvaco use some of the lignin from pulping as a polymer base for other market products, most of it is burned as a by-product.
A pulping digester has a fixed volume and throughput capacity. If lignin is a substantial part of the content of wood chips that fill the digester, it limits efficiency. So, if you can modify the lignin to cellulose ratio in wood so that more of the digester content is cellulose, you increase the amount of cellulose fibers in the digester and reduce the amount of chemicals and maybe the time to reduce the contents to wood pulp. Calculations indicate that altering the cellulose to lignin ratio could have significant value in the total cost of wood itself as well as the pulping efficiency to make a ton of paper. Thus, pine trees with reduced lignin content could have tremendous market value to pulp mills.

In addition, there is some initial evidence that a tree uses more of its resources to make lignin than it does to make cellulose. Lower lignin content has been shown to result in much more rapid volume growth, and growth enhancement is clearly something that appeals instantly to all tree growers. More work is needed to clarify this scientifically.

In the Southern United States, there are two major problems and one potential third problem associated with lignin reduction. First, most people manage their pine stands to produce a mixture of pulpwod and sawtimber. Sawtimber typically has a market value per unit that is about three times the value of pulpwod. In a forest that is managed to produce half its volume as sawtimber and half as pulpwod, sawtimber accounts for about 75% of the market value. Sawtimber specifications for construction lumber are based on strength and stiffness, and those attributes come in part from lignin that binds the fibers together tightly. If we reduce lignin content in order to enhance pulping, we risk devaluing trees for sawtimber. However, there are indications that this can be offset by genetic modifications so trees produce more syringyl lignin that is associated with hardwood species and less guaiacyl lignin typical of pines that is more difficult to remove through pulping. This could offer pulping advantages without reducing stiffness, but it doesn’t produce the advantage of the lignin to cellulose ratio in the digester. Clearly before commercialization, such products would need thorough study to ensure there are no significant downsides.

The second problem is that mills in the U.S. buy more of their fiber from a host of private forest owners and as sawmill residues than they grow themselves. This varies from company to company, but a ratio of about one third internally grown wood, one third open market roundwood and one third sawmill residues may be typical. The only portion of that where a company can directly control lignin content is what it grows on its own land as a mixture of pulpwod and sawtimber. The other two wood flows come from millions of independent sources. Furthermore, companies are selling parts of their forest land and opting for greater reliance on open market sources. A company could potentially isolate its own reduced lignin wood to feed separate pulping lines, but today mills don’t use separate wood and pulping streams for wood from sources that have even greater variation in usable wood content. It takes about six tons of pine thinnings compared to less than four tons of mature outer wood from sawmill residues to make a ton of Kraft linerboard. Even with that significant difference companies don’t use separate lines to process thinnings, residues and woods-run material.

Of course, for MeadWestvaco’s Brazilian Kraft mill that can provide up to 100% of its wood from perhaps 60,000 acres of pine plantations on its own land, that deployment problem doesn’t exist. If offshore markets like mills in Brazil are the only ones that are positioned to
capture the potentials of reduced lignin, then that adds to global challenges that already face the pulp and paper industry in the United States and Canada!

The third, potential, problem that I mentioned is that in some tree studies high lignin content has been associated with higher insect and disease resistance in trees. That hasn’t been fully quantified to my knowledge, but it’s another risk factor to be understood by tree growers.

Lignin reduction represents significant financial, production and biological interplays with both positive and negative results that require very thoughtful consideration by scientists, forest managers and wood products producers. Failure to completely assess and understand every facet can mean the difference between a resounding business success and failure.

The attribute of clearest value to all forest growers is rapid tree growth that accumulates more merchantable volume in shorter growth cycles. This may be accomplished by accelerated tree breeding as well as genetic engineering to enhance the ability to use growing site resources more fully and efficiently. Stress tolerance may extend the range of sites on which a species can be planted, and this is requisite for most of the U.S. hardwoods to become acceptable tree plantation species. Insertion of genes to create herbicide resistance or tolerance and genes to create insect resistance also help to further capture growth potential. These modifications enhance yield while reducing cost, they can be realized by anyone who grows trees, and they have relatively clear incremental values that can be calculated. They don’t change basic wood properties or market values. And these are the traits that catalyzed the initial interest in biotechnology by forest industry.

Other potential market values probably require more complicated genetic modification, and this adds time and cost but with more limited cost-benefit ratios. Growers of radiata pine, for example, would love to have the tree species produce straighter grain with less twist. It may not be possible to modify those traits with just one gene, and the market is confined to a relatively small area of plantations of that species in a few countries. That may be typical of many species where changes in wood formation and properties would have clear values.

Cold-tolerant eucalyptus could have enormous value in the United States. This region has no hardwood species that grow well in plantations over an array of site conditions. Cottonwoods come closest, but those species have low wood density and are limited to moist, fertile sites. Eucalyptus, like loblolly pine, grows on a wide array of sites and does well in plantations. Fiber traits and growth cycles of Eucalyptus suggest a tremendous potential value to forest growers and to the forest industry here if efforts are successful.

The list of potential benefits from genetic modification of forest trees is limited in its length and imagination so far. I’m curious that I rarely hear discussion of allelopathy and its potential to enhance the ability of trees to fend off competition. Allelopathy is a whole field of science in its own right, and there is immense knowledge of the ways that plants produce substances in roots or wood or leaves to fend off competing vegetation and insects. We know that walnuts have strong allelopathic traits, as does Ailanthus. We might view Bt as an application of allelopathy, but there doesn’t seem to be much more said about the broader potentials — or maybe I’m just not looking in the right places.

I wonder about the potential to find ways for trees to produce compounds such as those in bald cypress and redwoods and the heartwood of longleaf pine that repel wood rot? At a time when there has been a massive change in pressure wood treatment because of concern about the inorganic chemicals that are used to preserve wood, can we grow more species that yield lumber that is preserved with Nature’s own organic chemicals?
The problem with these kinds of values that I have mentioned is that they largely accrue financially to tree growers and/or processors but not to the public except in peripheral ways. And that doesn’t capture the public’s imagination. Like the values associated with herbicide resistance in agricultural crops, the public reaction is one of “the big companies get all the benefits and everyone else takes most of the risk.” That perception is reality to most people.

Canada has a focused biotechnology strategy developed by the government in partnership with various groups and they have been closely monitoring public attitudes through public opinion surveys over the years. The most recent survey was made last year and its key findings are informative.

The survey found that most Canadians view each biotechnology application on its individual merits on a case by case basis, using an implicit risk/benefit calculation that focuses on the marginal personal benefit from the specific application. Their fundamental question is “do the potential benefits compared to non-genetically engineer products outweigh personal risks to me and my family?” The larger and more personal the anticipated benefit, the more acceptable the risk is likely to be.

The Canadian survey also found that people ranked health applications of biotechnology the highest, with environmental applications in the middle range and with agricultural and food applications ranked much lower.

Similarly, in 2001 the Pew Initiative on Food and Biotechnology and the Society of American Foresters co-sponsored a conference to explore a broad range of views and perspectives surrounding the potential introduction of genetically engineered trees into forest ecosystems. One conclusion from that conference was that the developers of genetically engineered trees need to demonstrate products that have a clear value to end consumers and not just growers and processors.

Those two sources — one in Canada and one in the United States — suggest that when the public sees direct, personal value from forest biotechnology it is open to understanding and taking the risks. When the perceived benefit goes to others but the risk is to the forests they depend on for other things, they don’t want to even consider it.

Medical biotechnology confronts people in very personal terms. It involves drugs that cure or reduce the effects of dread diseases on individuals. Benefits are targeted to the consumer in very tangible ways. If I am diagnosed with a disease like cancer that has a distinct potential to kill me, or a disease like Parkinson’s or Alzheimer’s that can severely debilitating me, I’m already running a severe personal risk. Weighed against that, a bioengineered medical treatment that can cure me presents a value versus risk question that is a no-brainer.

Medical biotechnology confronts people in very personal terms. So far we don’t offer that kind of risk-reward equation in forest biotechnology.

So far we don’t offer the public that kind of risk-reward equation in forest biotechnology.

However, it is encouraging that in the last two or three years we are seeing more public references to facets of forest biotechnology that the public can relate to and in which people can see intrinsic, if not personal, value. Foremost among these is the potential for biotechnology to create resistance to American chestnut blight and perhaps ultimately lead to restoration of this marvelous American species. As Sharon Friedman with the Forest Service can tell you, in many quarters the restoration ecologists are getting far more attention today than foresters.
There is increasing public mention of other diseases that may be addressed through biotechnology, including beech scale complex, butternut canker, dogwood anthracnose, Dutch elm disease, sudden oak death and white pine blister rust. The Heritage Trees® Program here at the Institute of Forest Biotechnology is a clear, positive step in that direction. In June scientists at the Department of Energy Joint Genome Institute in collaboration with the Virginia Bioinformatics Institute announced they completed the genetic blueprint of *Phytophthora ramorum*, the pathogen responsible for sudden oak death.5 Hopefully this will lead to further progress toward an early understanding of this new tree disease and ways to address it successfully. These applications have an urban as well as a rural market potential and can appeal to people in terms of the trees in their backyards and city parks as well as in rural forests. That can begin to provide the public with a more personal sense of the value of forest biotechnology and receptivity to other aspects of genetic engineering in trees.

There are indications of broader acceptance of agricultural biotechnology during this past year. Those of you who receive the Meridian Institute’s daily news flashes via e-mail or who regularly monitor other sources have probably noted this, too. The Ecological Society of America has recorded a clear potential for forest biotechnology, logically subject to appropriate testing and safeguards.

On June 29 of this year the UN Food and Agriculture Organization’s *International Treaty on Plant Genetic Resources for Food and Agriculture* went into effect.6 A related UN report issued in the middle of June approved the use of genetically modified seeds and noted the greater potential for their benefit when the technology is extended more fully to the poorer countries. There has been activity in Africa throughout the year as African countries define conditions for greater use of agricultural biotechnology to provide more and better nutrition to people there.

In May, a report from the European Academies Science Advisory Council cited the need for more funding and a coherent strategy to enable European scientists to apply new genetic tools and methods to agriculture there.7 This echoed a similar expression reported by the European Commission in March, and in June, the European Research Commissioner endorsed a 20-year vision for the future of plant biotechnology in Europe that was drafted by a variety of stakeholder groups.8

There does appear to be a broad shift occurring in general public attitudes about biotechnology, although there remain many skeptics and others who are opposed based on ideology.

Finally, we need to consider forest plantations as the overall context for the use of genetically modified trees. In the southern United States and the Pacific North West, and in parts of the Lake States, forest plantations are more or less taken for granted and accepted as normal practice. Plantations there are associated with the restoration of forests from earlier clearing for agriculture. Globally, forest plantations are often associated with harvesting natural forests and their replacement with planted forests of exotic species.

The July issue of *Forestry Source* published by the Society of American Foresters in its Science and Technology section featured an article entitled *Domesticated Trees May Be the Future of Forestry*.9 But plantations in general, clonal plantations more specifically, and plantations of genetically modified trees in particular raise a whole array of concerns for conservation organizations and the public. Resolving those concerns is another major challenge to forest biotechnology.
That concept isn’t new. In the late 1990s a world Forest Vision arose from work done under the auspices of the World Bank and its WWF Alliance, from World Resources Institute and other organizations. Thoughtful individuals within the conservation community began to discuss the idea that 10 to 20 percent of the world’s forest area managed intensively in plantations could meet expected world wood requirements. That would leave extensive forests untouched by man or managed for other purposes that do not emphasize timber production.

In November 2000, David Victor who was then with the Council on Foreign Relations in New York and Dr. Jesse Ausubel of Rockefeller University published an article entitled “Skinhead Earth.” They outlined a very compelling case for intensively managed forest plantations on roughly one tenth of the Earth’s forest area and noted that the primary benefit of such plantations would be the values associated with the 90% of forests that are left for other purposes. The 10-90 or 20-80 concept is more difficult to apply here in the United States where about 75% of the forest is privately owned and actively managed, but on a global scale it has potential.

Two years later, David Victor and Ford Runge at the Council on Foreign Relations published a companion article entitled Sustaining a Revolution: A Policy Strategy for Crop Engineering. In that article the following quotation is particularly relevant to our interest today:

“We are concerned that today’s debate over genetically engineered crops has drifted away from reality, driven by short-sighted tactics rather than strategic thinking. On one side, some advocates of transgenics are so eager to see the method deployed that they pretend engineered crops are no different from earlier agricultural innovations; in fact, differences do exist, and some of them are substantial enough to require new types of regulatory oversight. On the other side, meanwhile, a vocal minority of detractors has amplified hypothetical risks in an all-out assault on the very concept of crop engineering. The most disturbing impact of their attack has been hobbling the application of the technology where its contribution to human welfare would be greatest: in publicly funded crop programs that benefit poor farmers and consumers in the developing world...”

There are some nongovernmental organizations whose opposition to tree plantations and genetic modification of trees is purely ideological and they are not open to discussion. But others in the conservation community have expressed openness to the idea although a lot of details need to be worked out to move from conceptual agreement to actual acceptance on the ground.

For the last four years I have been privileged to co-lead, with Dr. Nigel Sizer of The Nature Conservancy, an international group called The Forests Dialogue. Its steering committee is comprised of leaders from forest industry, conservation organizations, private forest owner groups, organized labor and a few other interests. The Forests Dialogue — TFD for short — has sponsored breakthrough dialogues on forest certification and forest biodiversity conservation. Next year we anticipate new dialogues related to illegal logging and to intensive forest management. We envision this latter dialogue will begin a series of thoughtful discussions about intensive management of natural and planted forests and the technologies that are needed to make such management technically and economically successful. This logically could extend to genetic enhancement from the use of genetically enhanced trees. TFD represents at least one starting point for the kind of dialogue that will clearly be needed to gain acceptance of clonal forests by probing workable “rules of the game” that meet the needs of various parties.

In conclusion, as we begin our discussions I continue to be very optimistic about progress and opportunities in forest biotechnology in North America and around the world. Remarkable progress is being made in the basic sciences of molecular biology and genomics, and every day
new discoveries are made about the function of genes in the plant world. Excellent progress is also being made in the related field of genetic engineering of plants. But we are still a long way from commercial implementation of forest biotechnology on a scale commensurate with investments that are being made. We must be a lot more imaginative in defining commercial potentials for genetically engineered trees and products. We must be more innovative in identifying uses of forest biotechnology that resonate with the public because of clearly understandable values. We need to be much more effective in communicating our ambitions to the public in ways that generate a greater sense of personal value and less sense of personal or social risk.

References

NEW CENTURY, NEW TREES
Biotechnology as a Tool for Forestry in North America

Where we have been and where do we stand today in forest biotechnology research and development in North America?
Setting the Stage for the Introduction of Forest Biotechnology

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Abstract
Six reasons for doing forest biotechnology, including some advantages and disadvantages of each, are presented. They are:

1. **Because we can.** Advances in genetics and molecular biology in the 20th Century made it possible to apply biotechnology to forest trees.

2. **Scientific curiosity.** Techniques of biotechnology allow us to better learn how trees are put together and how they work.

3. **Increase profitability.** Companies and others invest in forest biotechnology because they believe they can make money by doing so.

4. **Stay current.** To retain or gain the respect of colleagues, we need to do modern biology.

5. **Novel traits.** By introducing genes from different populations or even different species, properties not previously present can be produced in some clones or lines of trees.

6. **Improve productivity.** We may need to grow and harvest more wood on less land to support future human populations that are larger and/or with a higher standard of living.

Even though item 6 is controversial, it offers the best argument for gaining support from environmentalists and the general public in the application of biotechnology in plantation forestry.

Introduction
The term “biotechnology” came into common usage in the 1980s, and its several definitions continue to change. Broadly defined, it is anything that combines technology and biology. More narrowly defined, modern biotechnology focuses on such things as DNA-level analyses, transfer of single genes from a different species, and cloning by somatic embryogenesis.

Applying biotechnology in forests seems to be unusually sensitive. Forests have special characteristics associated with spirituality and aesthetics that don’t lend themselves to detached objective analyses of tradeoffs and values. Furthermore, most societies have long been accustomed to seeing and using domesticated crops and animals. But departing from the hunting-and-gathering mode of obtaining wood and other things from the forest became common only about 50 years ago, and many of Earth’s forests are still used by humans in a hunting-and-gathering mode. It is possible that recent and current hunting-and-gathering practices still viscerally affect many people’s perceptions as to what is appropriate in forests.

Biotechnology has become more controversial as the level of the technology has increased. For example, cloning of fruit trees by grafting is “low-tech” biotechnology, long established and not particularly controversial. Cloning of animals by the production of embryos in laboratory cultures is “high-tech”, recent and controversial. Planting trees to reduce erosion, modify lo-
cal climate, and/or sequester carbon are generally accepted low-tech biotechnologies. But successfully transferring single genes from one species to another is high-tech, very recent and, for some people and organizations, highly controversial. It seems that modern high-tech genetic modification of forest organisms is an issue of greater concern than, for example, the use of high-tech radiotelemetry to track the behavior of owls in the forest. In other words, it is the high-tech genetic modification of forest organisms that is causing great concern; various applications of high-tech to forest organisms that result in little or no genetic change are causing little or no concern.

Because it is controversial, it is important that those who wish to successfully practice it obtain what may be called a “social license” to do so. At the beginning of this paper, I mention six reasons for doing modern forest biotechnology and, in considering some of their advantages and disadvantages will focus on how they affect this important social license. The first five reasons, and many of their advantages and disadvantages, are familiar to many in this audience. The sixth, I think, is not only the most important, but it is often overlooked when considering whether, why and where to apply biotechnology to forest trees.

1. **Because we can.** Modern forest biotechnology has been built on centuries of scientific and technical advance. The pace of these advances accelerated during the 20th Century, and kicked into very high gear with the characterization of DNA and the understanding of how it works. It is obvious that being able to do it is fundamental to doing it.

   **Some advantages.** A great advantage of knowing that something can be done is that people no longer wonder whether it can be done, but focus instead on how to do it better, and on where to do it. As has been the general case with modern biotechnology, as experience is gained and advances are made, the things we can do with forest trees can be done more quickly and efficiently.

   **Some disadvantages.** There is a school of thought that proposes that if this human species can do something, it probably will do it. If we can fly to the moon, will we? If we can make a nuclear bomb, will we? If we can clone a rich and powerful person, will we? There is a distrust of science, or more specifically, of the use of science, that cannot be ignored. That we will do forest biotechnology simply because we can, while that reason has importance and merit, it is by itself an inadequate and perhaps counterproductive rationale that impedes the social license to do it. We need better reasons than that.

2. **Scientific curiosity.** For many at this meeting, this is the primary and sufficient reason for applying biotechnology to forest trees.

   **Some advantages.** Biotechnology provides powerful tools for learning how trees work and how they are put together. For example, the improved ability to clone many species allows us to take the same genotypes and grow them in many copies in contrasting environments, thus better understanding the contributions and interactions of genetic makeup and environmental variables to expression of various traits. Genetic analyses at the level of DNA allow us to answer such questions as how many genes a species has, how they are arranged and organized, and how they interact to produce different expressions of traits of interest.

   **Some disadvantages.** Some reviewers of this idea indicated that scientific curiosity would not be a sufficient reason for some elements of the public. It was felt that using public funds and perhaps exposing ecosystems to unknown risks to satisfy a bunch of curious scientists could not be justified. To justify the costs and risks can be hard to do with people who view curiosity-driven scientists as useless, dangerous, and parasitic on society. One needs to show as a result of satisfying such curiosity that there would be substantial value
to humans, and/or better protection of ecosystems and ecosystem processes.

3. **Increase profitability.** It would be nice if benevolent governments or well-endowed non-profit NGOs adequately funded and otherwise supported R&D for forest biology. However, the trend seems to be in the other direction, and as market forces increasingly direct investment, it is increasingly left to private enterprise to fund such R&D. For such investments and support to occur, there must be reasonable expectation of profit.

**Some advantages.** In general, for-profit organizations must be and are more efficient than are organizations not dependent on self-generated funds. New technologies are often applied less quickly and less aggressively in organizations working for the public good than in organizations seeking to use them for profit. Such profits generally come from increased efficiency in producing established products, for example by reducing the cost of brush control in plantations through herbicide-resistance in the crop trees, or increasing the yield of wood pulp by modifying lignin content. They may also be sought in making entirely new products by engineering trees to grow and produce things not previously possible.

**Some disadvantages.** Many biotech scientists are seen as beholden to commercial interests, perhaps at the expense of candor or even truth. This has led to a suspicion that an uncertain amount of worrisome information may be protected by confidentiality clauses. Such suspicions can negatively affect the social license to apply biotechnology to forest trees.

Mark N. Cohen, University Distinguished Professor of Anthropology at SUNY, recently published a thoughtful article on how resources are allocated. As society became organized, political and social forces have removed supply from a direct dependence on demand. Thus, organizations that control technology can manipulate it to control supply of such things as food or wood, even though there is pent-up demand. Intellectual property rights, with accompanying secrecy and/or patent protection, impede the free flow of information and can restrict overall production in the interest of protecting market share and profit.

In fairness, it should be noted that some non-profit organizations, in pursuit of various agendas through such things as obstructive litigation and regulation, can also block or delay new technologies that could otherwise increase the supply of more and better wood.

Under either form of obstruction, it is the poor who are denied adequate amounts of wood and wood products. A 20 October 2004 open letter under the auspices of the International Consortium of Agricultural Biotechnology Research to FAO notes how the needs of the poor require some attention.

4. **Stay current.** In all fields of science, it is important to keep up with current concepts, methodologies and knowledge. It is clear that modern biology involves a lot of concepts and tools of modern biotechnology.

**Some advantages.** Besides the clear scientific and professional advantages of staying current, there are psychological advantages as well. Deans, CEOs and colleagues tend to respect cutting-edge scientists, and look down on those doing “old-fashioned” biology.

**Some disadvantages.** It is common for a new discipline, such as molecular biology to not only occupy center stage, but to result in the neglect of older but still-important disciplines. As an example, in forest genetics and tree-improvement, most new hires are molecular biologists. Not only are previously established field experiments being neglected, there is some suspicion that there is a shortage of field-savvy scientists to establish, monitor and evaluate the important new field trials of genetically engineered trees. In some tropical and subtropical regions, it has been noted that bright new people are attracted to high-biotech approaches to tree improvement, in part because these are conducted in comfortable air-
conditioned labs rather than in hot, humid, pest-infested forests. While that is clearly an advantage to the young scientists, it may be a disadvantage for the enterprise as a whole.

5. **Novel traits.** While biotechnology and genetic engineering can contribute to many established scientific and tree-improvement practices and goals, the ability to introduce genes and thus traits that do not occur in a population or species is a new tool in the grasp of humans. Suddenly, the genetic library of Earth’s entire biota becomes a source of information-laden DNA that can possibly be used to augment the traits already richly available in forest trees.

**Some advantages.** For traits that could be accessed sexually, transgenic insertion of one or a very few genes has the great advantages of speed and cleanliness. For example, to move genes resistant to chestnut blight from Chinese chestnut to American chestnut can be and has been done by hybridization and backcrossing. After four cycles of breeding, namely the hybridization and 3 backcross generations, The American Chestnut Foundation has selected resistant trees that are 15/16 American chestnut. But 1/16th of a genome is a lot of genes, and they affect countless traits and interactions. It will take many more generations of backcrossing to further dilute and eventually sort most of them out. Transgenic engineering provides an opportunity to insert into pure American chestnut the one or few Chinese chestnut genes conferring resistance, without all the accompanying genetic baggage affecting growth rate, wood quality, nut quality and myriad other traits.

Forest biotechnologists have borrowed a system from agriculture, and successfully inserted the “Bt” gene from *Bacillus thuringiensis* into poplar clones, thus acquiring resistance to larvae of lepidopterous insects that was not previously present in poplars. It is too early to tell how much can be realized by taking genes from very different organisms and incorporating them in forest trees. Some pretty amazing things can be imagined.

One might also remove or repress a trait using modern biotechnology that could not have been removed or repressed by breeding. Eliminating sexual reproductive function has at least three important advantages. (1) Because it would impede the “escape” of transgenic constructs by seeds or pollen, it would be an important step in obtaining the social license to deploy transgenic engineered trees to plantations and forests. (2) It might result in a greater harvest index of wood if biomass usually expended in pollen and seeds were allocated instead to the rest of the tree, and especially if it could mostly be directed to bole wood. (3) By using members of the same “macroclone” that differ only in their sexual competence, forest scientists can finally accurately assess whether and how much biomass is diverted to sexual organs at the expense of other parts of the tree.

**Some disadvantages.** Inserting transgenic constructs is not always as “clean” as we would like. Genetic damage occurring at insertion sites is a risk with current technology. Sometimes additional DNA is passively inserted along with the characterized desired DNA. This leads to the possibly serious problem of cryptic and uncharacterized variation, which is difficult to deal with because the scientists monitoring unwanted effects can’t know what they are looking for. Subtle, delayed-action effects remain a possibility. For forest trees, a delayed-action loss of health could be catastrophic, particularly if it involves most plantings made over a number of years in a region. It may be a much underestimated hazard.
While some critics are uneasy about any manipulation of “Mother Nature” in forests, they are perhaps the most concerned about the movement of genes from other taxa into forest trees as being both unnatural and dangerous. While some of the ecological dangers proposed are highly speculative (and thus hard to disprove), the uneasiness or even rabid opposition they produce are substantial impediments to gaining and maintaining the social license to “improve” forest trees. This opposition, whether reasoned and informed, or not, translates to a major disadvantage in creating novel traits by transgenic engineering.

6. **Improve productivity.** Warnings of “timber famine” have been issued before. While they have occasionally been correct locally and for short times, we have until now always had more than enough wood to satisfy most human needs. But that may not always be true.

**Some advantages.** Besides being likely to increase profits, there are 3 conditions that would make improved productivity a reason to support forest biotechnology. (1) If Earth’s human populations indeed will need more wood than can currently be produced. (2) If decision-makers and the general public accept that as a likely possibility. (3) If modern biotechnology can substantially add to productivity. If these 3 conditions are satisfied or likely, then the need for more wood than is currently able to be grown is the most powerful argument for granting the social license to apply biotechnology to trees deployed to our forests and plantations.

**Some disadvantages.** Decision-makers and the general public may not accept or even consider the possibility that we will soon need more wood; or, modern biotechnology may not be able to contribute much to the solution of the problem even if the need is recognized. In these scenarios, the other 5 reasons for doing forest biotechnology may not be sufficient to obtain the social license to do it.

**The likely future need for wood by Earth’s human populations**

Because the near-future need for much more wood than is now being grown and available for harvest in Earth’s forests is controversial, this crucially relevant issue is explored here in some detail. The importance of this problem depends in part on how large Earth’s human populations will be, and on the standards of living they will enjoy or endure.

Earth’s total human population has doubled twice in the 20th Century, and is now over 6 billion people. Projections of future total population size vary widely, from about 4 billion people mostly living like present-day Americans, to over 24 billion people mostly living pretty desperately. Many projections predict stabilization at about 9 or 10 billion around the year 2050.

People have long used wood, and it seems likely that they will continue to do so. If they continue to use wood at about the present rate per person, future needs for wood can be estimated by just multiplying current per-person use by projected numbers of people. But it is more complicated than that.

Americans currently use about 4 times as much wood per person as the average for all peoples on Earth. Thus, if that low projection of about 4 billion people were to be living like today’s Americans that would require an enormous increase in wood production. On the other hand, if population again doubles twice in the 21st Century, most of those 24 billion people may be living pretty much like rats, and per-person wood use is likely to be low.

If, however, one of the middle projections comes true, two things seem likely to have been important in changing population dynamics leading to stabilization in regions now experiencing increases in human populations. One is the education and empowerment of women, not the topic of this talk. The other is a rise in standard of living. With few exceptions, when standard
of living rises, birth rate falls but per-person use of wood increases. One can argue whether increased use of wood is a result of an increase in standard of living, or whether increased access to wood contributes to a raised standard of living. Whether either or both are true, the relationship seems strong. So, by 2050 in this scenario, not only will most of those additional 3 or 4 billion people be using wood, the 9 or 10 billion of Earth’s total population will be using more wood per person, on average, than Earth’s 6 billion people do today. That is also an enormous increase in demand for wood.

It is often argued that technology will find replacements for wood. That may prove to be true. The current replacements are various metals, bricks and cement, various alternative fibers, plastics, and reconstituted wood. With very few exceptions, all of these replacements require more energy, introduce more toxic materials into the environment, and emit more greenhouse gases in their extraction and manufacture than does solid wood. If energy becomes more abundant and less expensive, and inexhaustible sources of alternative raw materials are found, then per-person needs for wood will be reduced by substituting these alternatives. This would probably result in the unintended consequence of a warmer more-toxic world. But an alternative prediction is for a future where energy becomes more expensive and non-renewable raw materials are less available. In that scenario, wood will increasingly substitute for those other products, per-person use of wood will be even higher, and Earth will probably be cooler and less toxic.

California imperialism, the New Zealand Forest Accord, and the Maine Triad

If biotechnology and, particularly, modern genetic engineering are to be applied to Earth’s future forests, an important question is “where?” “Where” seems likely to be mostly in intensively managed plantations, with applications in extensively managed forests and in reserves much less common. Three case studies are presented with implications for all of Earth’s peoples and forests.

California: For most of the first 100 years after gaining statehood, California was a net exporter of wood and lumber. California has excellent forest sites, the best native conifer species for wood production on Earth, and favorable climates for forest growth. Yet, starting in about 1950, California became a net importer of wood and wood products. Values of water quality, wildlife, and aesthetics were given higher priority than wood production.

California’s forest-allocation issues were sorted out in a legal and political climate that can be characterized as divisive, contentious, litigious, counterproductive and economically draining. This did not necessarily lead to healthier forests, however. As one recent example, when San Bernardino County was trying to remove sufficient insect-killed dead and dying trees to reduce the developing fire hazard, they had to cut many trees at great expense. Since there were no longer any sawmills in the region, they then hauled the logs to safe places and incinerated them. They used a great deal of natural gas to do so, thereby adding substantially to cost and to the local plume of greenhouse gases.

Meanwhile, by 2002, California had become an 80% net importer of wood and wood products, and California activists were trying to stop all logging on its 17 National Forests. Their reasoning, at least in part, is that California can afford to, and thus should, protect its forests from the various real and perceived negative effects of logging. A strong case can be made that California has become Earth’s worst wood imperialist. “Imperialist” because California...
uses its economic and political power to acquire and import other peoples’ wood resources. “Worst” because, unlike states such as Iowa or Kansas: (1) California uses so much wood; (2) because it has the forest sites, species and climate to supply much or all of its needs for wood from its own forests; and (3) because it collectively chooses not to harvest from its own forests most of the wood it uses. California thus exports many real negative effects of logging to other regions and nations. In many of them, the real effects of both legal and illegal logging on species extinctions, on biodiversity, and on wood supply for local poor peoples are much more severe than the real effects that would have been incurred by harvesting equivalent amounts of wood in California.

**New Zealand:** New Zealand’s early history has much in common with California, and New Zealanders pay attention to developments in California. Unlike California, in the 1920s they began a plantation program to assure wood self-sufficiency.

To avoid the problems occurring in California, in 1989 leaders of the environmental and forestry communities began to work together to produce the New Zealand Forest Accord. It was signed in 1991 and, while not perfect, it continues to work well. Among other things, it (1) recognizes the important values of New Zealand’s remaining indigenous forests and the need for their protection and conservation; (2) recognizes that plantation forests are an essential source of perpetually renewable fiber and energy, providing an alternative to the depletion of natural forests, and (3) acknowledges the mutual benefits from this accord between wood-production forestry enterprises and conservation groups.

In 2004, while California foresters are spending much of their time preparing for and in litigation, New Zealand foresters are spending that time growing trees and husbanding forests.

**Maine:** Meanwhile, in northeastern U.S. forests, an analysis indicated that 3 times as much harvestable wood per hectare could be grown in plantations as was being grown in extensively managed forests. This led M. Hunter and his several colleagues to propose a “triad” approach for thinking about forests in Maine. It was recognized that forest allocation spans a continuum from remote virgin forests to intensively managed plantations. For conceptual clarity, this continuum was divided into 3 sections. In 1996, 2% of Maine’s forests were in parks and reserves, 6% was plantations, and the remaining 92% was being extensively managed with some commodity production. It was noted that the wood from that 92% was mostly harvested in a hunting-and-gathering mode, with highgrading within species and changes of species composition in those forests being all too common.

Many values of reserves with few or no human impacts are already recognized. Human-caused genetic modifications will be minimal in such reserves. Furthermore, although many details and interactions of species and processes in such reserves are not well known, it is unlikely that all or even many of the values and ecological processes maintained in minimum-impact reserves can be duplicated in extensively managed forests. As of 1996, Maine appeared woefully short of sufficient parks and reserves.

It was suggested that, if more of the extensively managed forest sites were instead managed intensively as plantations, three times as much area could be withdrawn from commodity pro-
duction and placed in parks and reserves, with no change in the sustainable annual harvest of wood. By upping the plantation area from 6% to 8.5%, the reserve area could be increased from 2% to 9.5%, leaving 82% of Maine’s forests being extensively managed. By putting more than the suggested additional 2.5% of forest into plantations, Maine could change from being a net importer of wood to being wood self-sufficient or even a net exporter to forest-short places such as Iowa and Kansas.

**Planet Earth**

The high-impact genetic technologies, namely tree-improvement, clonal forestry and modern genetic engineering, will almost exclusively be applied in plantations. From the standpoint of wood production, most of the genetic changes will be positive, although one can surely expect some setbacks. The unintended consequences of these technologies are properly a concern, and it will require good monitoring and good management to minimize them.

Meanwhile, it seems important to consider the needs of future human populations with aspirations to decent standards of living, and desires to protect forest ecosystems and non-human members of forest communities. These goals are well served by the strategy of reallocating substantial additional areas of forest land from extensive management to minimally managed reserves and to intensively managed plantations. A recent United Nations’ FAO inventory found 3,980,000,000 hectares of Earth’s land in forests, of which 95% is still more-or-less natural forests and 5% is plantations. There is currently a global trend towards greater reliance on plantations as a source of wood. The purposefully applied Maine Triad strategy seems a useful model for much of the world.

Will modern biotechnology be permitted a role in supplying future wood? First, can the modern biotechnology techniques available today or in the near future be effectively used to substantially increase the productivity of intensively managed plantations? If so, will decision-makers allocate substantial effort to initiatives targeting such increased productivity? If so, then it seems likely to be useful for some leaders in forest biotechnology to make common cause with responsible conservation leaders and organizations. At least 3 goals seem good candidates for such common cause:

1. **Raise the standards of living for most or all of Earth’s peoples, thus helping to stabilize human population size.**
2. **Reduce energy consumption and consumption of non-renewable resources, while continuing to supply the resources underpinning decent standards of living with more wood and wood products.**
3. **Allocate substantially greater areas to forested parks and reserves, free of the pressures to extract wood and other commodities.**

I close by invoking the “*precautionary principle*” in a perhaps unusual way. As usually applied it cautions that, if there is even a low risk of something going seriously wrong with a proposed course of action, one should not do it. But a failure to have available resources to support Earth’s human populations in a few decades may and probably will result in degraded standards of living and continued rapid growth of many of those populations. Even if such an outcome is not certain, it seems likely enough to invoke an inverse precautionary principle. To do nothing now risks extensive catastrophe for the near-term human populations on Earth, as well as for the natural ecosystems they will in desperation raid. Even though that scenario
might be avoided by creative new technology finding sustainable new non-wood resources, to do nothing now to increase the renewable wood resources for mid-21st century risks disaster. Because it seems at least plausible that in a few decades needs for wood will substantially exceed its availability, and because it takes decades for additional forests and/or better trees to grow, solutions must be considered and implemented soon. The inverse precautionary principle thus cautions, or perhaps demands, that we should be planning and doing things to increase that renewable wood resource by developing and planting more and better trees now.

Because it seems at least plausible that in a few decades needs for wood will substantially exceed its availability, and because it takes decades for additional forests and/or better trees to grow, solutions must be considered and implemented soon.

References

Acknowledgments
For their valuable and valued help, I acknowledge with thanks Steve Anderson, Rowland Burdon and Bob Kellison.
Forest Biotechnology in the “Omics” Era

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Abstract

Advances in biotechnology are most evident in the field of medicine. However, the forest biotechnology sector has expanded rapidly over the past decade, and molecular markers are now available for use by tree geneticists. In addition, the forest sector is one of the sectors targeted by national governments for genome research. The production of genetically modified trees is now a reality and the commercial use of GM trees is just around the corner. In this article, we will describe recent innovations in the field of forest tree biotechnology and their possible applications. We will also discuss the many opportunities created by forest genomics.

Introduction

With all the increasing pressure they are facing can forests remain a source of diversified life and a productive environment capable of meeting the needs of all of humanity? What can we do to ensure that the answer to that question is yes? Of course, our efforts will have to take various forms, because there is no one magic solution to all of the problems caused by man to his environment. We will describe some of the solutions offered by biotechnology and forest genomics in the context of the latest developments and advancements expected in the near future and the framework in which they should be used.

In the next few decades, world demand for wood products of all types will, without a doubt, rise (Fenning and Gershenzon 2002), although the demand for industrial wood is likely to rise at a slower pace (Sedjo 2001, Whiteman and Brown 1999). Although the rate of world population growth fell substantially from 1975 to 2000 compared to the period from 1950 to 1975 (from 64% to 48%), it is still estimated that by the end of the 21st century the world population should exceed 11 billion. Our natural ecosystems are subject to increasing direct and indirect pressures, as can already be seen in some regions. In 1999-2000, some 9.4 million hectares of forest were lost (FAO 2001).

There are many unique species that find the resources needed to survive and reproduce in the forest. Some of these species, which are likely to disappear, provide or have the potential to provide essential food and medicine for humans. As a result, there is growing pressure to protect a larger part of our natural ecosystems. This can only be achieved to the detriment of industrial uses of the forest. Yield per hectare must therefore be increased on the remaining territory to meet the population’s needs for wood products of all sorts and to ensure the energy security of countries that use wood for heating. The energy needs of developing countries are expected to rise by 2.5% a year. If these needs are met by conventional sources, carbon dioxide emissions are likely to increase, thereby accelerating climate change. Fortunately, trees are able to sequester carbon and help humans in their strategies to mitigate the impacts of climate change.
It is becoming more and more widely accepted that the use of plantation forestry will not only be desirable but will be essential to reconciling the many objectives described above (Binkley 1997, Boyle 1999). The designation of areas for intensive wood production and the use of fast-growing species and varieties are more likely to make it possible to more effectively meet the demand for wood products while reducing the impacts of harvesting in natural ecosystems (Vincent and Binkley 1993). The current area of plantations throughout the world is estimated at 187 M ha (FAO 2001). They currently provide approximately 35% of the world’s industrial wood needs (Table 1, Sedjo 2001), and that percentage could rise to 75% by the year 2050, whereas harvesting in old-growth and second-growth forests should decline considerably (Sedjo 2001). To meet the world demand while minimizing the areas set aside for industrial plantations, it is essential to take advantage of all scientific advancements to identify the sites with the best potential and to develop high performance varieties. This will be possible by integrating new biotechnology and genome tools with conventional genetic improvement techniques. In addition, it is within the framework of land zoning and industrial plantations that a number of essential biotechnologies have the greatest chance of being accepted by society.

**Table 1. Percentage of industrial wood harvested as a function of forest type (Sedjo 1999)**

<table>
<thead>
<tr>
<th>Forest type</th>
<th>Industrial wood harvested (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old-growth forests</td>
<td>22</td>
</tr>
<tr>
<td>Second-growth forests, extensive management</td>
<td>14</td>
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<tr>
<td>Second-growth forests, intensive management</td>
<td>30</td>
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<tr>
<td>Industrial plantations of native species</td>
<td>24</td>
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<tr>
<td>Industrial plantations of exotic species</td>
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</table>

**Principal forest biotechnology tools**

Over the past few decades, conventional tree improvement programs, which involve selection, genetic crosses and recurrent testing, have been used around the world to improve plantation yields and have certainly proven useful. Several dozen species, most of which belong to the genera *Pinus*, *Populus*, *Eucalyptus* and *Picea*, are now subject to genetic improvement programs. There have also been major advances in recent years in the development of biotechnology tools that can be incorporated into genetic improvement programs and can potentially accelerate the progress sought.

For most people, biotechnological advances are evident only in a few sectors of human endeavour that attract wide media coverage. For example, progress is reported almost daily in the development of new drugs and vaccines. Advances in the petrochemical processing sector also garner positive media attention. This industry, which operates under the pressure of limited resources and the need to take account of environmental costs, recognizes the potential of biotechnology for several sectors of activity (fine chemistry, polymer, and hydrocarbons such as ethanol). Unfortunately, the recognition of the potential of biotechnology in the forest sector is much more limited. However, it is becoming an increasingly important component of the processing sector, such as pulp and paper production, and it also plays an important role in various stages of the production chain, from planting to harvesting.
One of the first applications of biotechnology in forestry was the inoculation of seedlings with symbiotic organisms (specifically mycorrhizae) with the objective of increasing seedling growth. Since then, tremendous progress has been made in the field of forest biotechnology, which currently focuses on three main areas: plant propagation, transgenesis and genomics, including the use of genetic markers for specific purposes (Yanchuk 2001).

**In vitro culture**

The first area consists of *in vitro* culture. This technique involves propagating plant tissues (units as small as a cell) in a controlled environment free of microorganisms. An entire tree can be regenerated from a single cell. *In vitro* culture can be used to reproduce seedlings and to cryopreserve cell lines from which it will be possible to regenerate other copies of the same seedlings in the future. In *in vitro* plant culture, regeneration occurs via two main pathways: organogenesis and somatic embryogenesis. Organogenesis is the regeneration of plants through organ formation on an explant or from cell masses, and for somatic embryogenesis it is done through the formation of embryo-like structures (Figure 1). Organogenesis has been the method of choice for species such as poplar and eucalyptus, and embryogenesis has been used very successfully with conifers (Park et al. 1998). Both processes provide the means to clonally propagate large numbers of elite trees for research and reforestation. In addition, it

Figure 1. Somatic Embryogenesis (SE) in Conifers
can be scaled up to an industrial level with rapidly declining costs (e.g., mass production of loblolly pines by CellFor Inc.), by identifying the key genes involved in this process (genomic approach). One drawback of somatic embryogenesis is that it is fully applicable only using juvenile material as initial explants (embryos but difficult to carry out with needles). To capture maximum gains a two-step procedure must be established. Firstly, while testing new lines produced with replicated clonal trees, tissue lines must be cryopreserved. Secondly, once the best clone has been identified after a few years of testing, cryopreserved tissue of the best lines are put back into in vitro culture for tree multiplication and propagation. In vitro culture is also essential to genetic engineering or transgenesis work because it provides the material on which the technology can be carried out.

Transgenesis
The second major area is genetic engineering or transgenesis. A traditional cross between two individuals permits the exchange of chromosome segments carrying one or more desired genes. However this genetic combination produces individuals that have genotypic and phenotypic characteristics specific to each parent. Traditional breeding has been used to produce agricultural plants, as we know them, and trees produced under breeding programs using generative methods. Through the use of transgenesis, it is possible to introduce one or more perfectly characterized new characters without, in theory, adversely affecting the overall genetic make-up of the plant. This approach also offers the possibility of overcoming the genetic barrier between species, in a relatively shorter time frame than through conventional tree breeding. Once transgenesis is performed at the cell level, in vitro culture techniques can be used to regenerate the entire tree.

Main applications of transgenesis

Modification of lignin
After cellulose, lignin is the most abundant organic compound in the biosphere and makes up 15 to 35% of the dry weight of trees. Extracting lignin from wood is a costly and polluting stage in pulp and paper production. It is now possible to develop transgenic trees that have lower lignin content but do not have unfavourable physiological characteristics. Biochemical pathways in lignin synthesis have been the subject of numerous investigations, and several genes responsible for the enzymes involved have been characterized (Tzfira et al. 1998, Merkle and Dean 2000). By manipulating the expression of these genes, it has been possible to modify the lignin content or structure. Some of the transgenic trees contain modified or reduced lignin, which makes it possible to reduce the use of chemicals in pulp and paper production.

Resistance to forest pests
The use of genetic engineering to improve tree resistance to insects and microbial pests has been the subject of investigation in several laboratories. For example, at Natural Resources Canada (NRCan), researchers introduced the gene corresponding to the toxin Bacillus thuringiensis (B.t.) into white spruce (Picea glauca [Moench] Voss). White spruce is susceptible to spruce budworm (SBW), an insect that has caused the defoliation of large areas in Canada. The transgenic trees obtained were tested for their toxicity to SBW and complete re-
Resistance was observed in several trees (Peña and Séguin 2001). This research is part of the development of a research model and is not aimed at the commercialization of such a product. Similarly, in several parts of the world, fungal and bacterial infestations cause substantial forest losses. These losses are very often underestimated, as compared to the damage caused by insects, because the damage is less visible. However, it is possible to induce resistance by introducing genes associated with the production of antifungal or antibacterial proteins (e.g., endochitinase, PPO) (Séguin 1999). Various approaches, which are currently at the experimental stage, will be used to assess the effectiveness of these strategies for forest trees (Peña and Séguin 2001).

**Rules governing the dissemination of genetically modified material**

As mentioned above, the development of the first transgenic trees, in particular conifers, dates back to the early 1990s. Since then, several research teams in North America and Europe have conducted field trials of the transgenic trees (Mullin and Bertrand 1998). NRCan established the first field trial of transgenic trees in Canada under confined conditions (Hay et al. 2002). In Canada, the establishment of such experimental designs is governed by strict guidelines issued by the Canadian Food Inspection Agency. Overall, the results have shown that the transgenic trees have no abnormal characteristics. The field trials, along with research on the potential environmental impacts of the transgenic trees, are of critical importance in establishing the scientific basis required for documenting the safety of this material (Strauss et al. 1995).

**Structural and functional genomics**

By definition, genomics is the study of genomes. It is no longer limited to the study of a small group of genes for the purpose of gaining a better understanding of a given physiological process, but rather of using genomics methods to determine how the expression of several thousand genes can explain a biological phenomenon. With respect to forest trees, only one full systematic genome sequencing project has been completed and it deals with poplar. The initiative, undertaken by the U.S. Department of Energy (genome.jgi-psf.org/poplar1/poplar1.home.html), is aimed at sequencing the genome of a species of the genus *Populus*. Poplar, like *Arabidopsis thaliana*, is used as a model organism by molecular biologists given the relatively small size of its genome, the availability of several hybrids resulting from controlled crosses and its favourable response to genetic transformation techniques. The poplar genome is four times the size of the *Arabidopsis* genome and about forty times smaller than that of pine. In conifers, systematic genome sequencing is, for all practical purposes, impossible due to the large size of their genomes. For example, the genome of *Picea glauca*, a species of major economic importance in Canada, is almost 10 times larger than the human genome.

Although obtaining the complete genome sequence of conifers is currently unthinkable, it is possible to have access to sequences of genes expressed in a particular tissue at a given time, or...
Although obtaining the complete genome sequence of conifers is unthinkable, it is possible to have access to sequences of genes expressed in a particular tissue at a given time, or expressed sequence tags (ESTs).

In trees, the profile of the genes expressed in the leaf is different from that of the genes expressed in the meristems of the trunk. The establishment of leaf EST banks, for example, can shed light on the major players in photosynthesis. A number of research programs have been initiated to identify the sequences of genes involved in various physiological processes of woody plants, primarily wood formation (see Table 2). This gene catalogue of sorts is an important tool for forest genomics. For example, the scientific data can be used in genetic mapping and functional genomics and can serve as a molecular tool to assist in the selection of individuals with desired characteristics.

What genomics offers

As previously mentioned, genomics is the study of all genes of a given species, their arrangement and their functions. In summary, genomics is used to establish relationships between the presence and the activity of one or more genes and a given phenotype. Advances in forest tree biotechnology have been slow due to the biological complexity of trees. To date, the knowledge acquired in agricultural biotechnology (resistance to insects and herbicides tolerance) has been applied to some forest trees. However, the same cannot be done for more complex mechanisms, such as growth and flowering, wood formation and multiple resistances to forest pests.

Forest genomics will likely focus on several important areas:

1) Pest resistance, due to the growing problems that are associated with the introduction of exotic diseases and that could be exacerbated by climate change and the increased flow of goods around the world;

2) Desired silvicultural characteristics for the domestication of trees and the establishment of plantation forestry. The objective will be to improve the growth, shape and properties of wood from plantation trees in order to maintain or increase the value of end products;

3) Control of flowering to prevent the dissemination of transgenic plant material into natural environments in the case of transgenic plantations and to increase growth by redirecting energy transfers associated with flowering to vegetative structures;

4) Wood formation and lignin deposition in order to develop a resource that is more compatible with our needs. Wood formation is a highly complex phenomenon that involves several cells (plant cell wall formation, cell division) and biochemical (cellulose formation and lignin deposition) mechanisms. Genomics will help to shed light on these mechanisms.

Once the gene catalogue for poplars and certain conifers is completed, it will be possible to transfer the knowledge gained to other less economically important species or to species given priority by developing countries.

Equity in access to biotechnology

Although genome research is essentially restricted to developed countries that have necessary financial resources, it is clear that the technological developments will have an impact on forest productivity throughout the world. Once the gene catalogue for poplars and certain conifers is completed, it will be possible to transfer the knowledge gained to other less economically important species or to species given priority by developing countries. If
wood formation is the subject of intensive research, the results of which are eventually protected by patents, opportunities to search for drought resistance, for example, will be within easy reach.

Genomics tools will facilitate the domestication of trees in order to increase the supply of raw materials and protect natural forests by reducing harvesting pressures on them. The optimization of the various techniques described in this article (in vitro culture, genetic markers, transgenesis, etc.) will facilitate their application to different forest tree species and could be an important tool for restoration of lost species. For this to happen, ongoing co-operation between the scientific communities of industrialized and developing countries is essential. This can only be achieved through the creation of a technological assistance fund aimed at promoting north-south co-operation.

**References**


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Forest Biotech: A Hammer Unsuccessfully Seeking Nails?

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Technology development and forest biotech reminds me of the expression- “if all you have is a hammer, everything looks like a nail.” Forest biotech has been on the scene for a while and yet adoption by users is the exception rather than the rule.

We have to ask the question “what real world problems can forest biotech realistically help solve?” and the question that is seldom, if ever, asked “what are the competing technologies to solve the same problem?” Is solving the problem this way as environmentally, socially and economically desirable as other technologies? Unfortunately, the gap between academic researchers and users of the technology exists- what a scientific panel thinks might be useful is not the same as what users are willing to pay the extra costs to receive. Rationales for the use of the technology tend to come from statements of researchers rather than a logical thought train by people or organizations seeking answers to real-world problems.

Forest biotech using forest trees suffers from the same economic problems as other early investments in tree growing. Yes, genetic changes can be made, but it takes a while to see if they are going to work over a rotation. For a short-rotation species that is not a problem, but for longer-rotation species that can be a serious problem. Analyses of risk and uncertainty and understanding the economic and social needs of industry and landowners are critical to finding appropriate uses and the eventual adoption of this technology.

Forest Biotechnology: A Joint Effort between Industry and Academia

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Healthier trees and more and better wood are possible through biotechnology. But at this stage, where tremendous efforts have been made in improving public acceptance of transgenic plants, we must have a clear focus on the traits needed to be engineered today to be ready for tomorrow. Indeed, successful cases in genetically engineered traits in trees are still scarce and none of these has proven its worth for commercial benefits. More and better wood is nice but perhaps illusive. Depending upon the end uses, for instance, wood with less lignin may be considered better wood by the pulp and paper industry but not by the lumber industry. High lignin, therefore, high density wood is better for lumber. High lignin wood may also be desirable to certain less energy self-sufficient pulp mills that normally require more lignin in the waste stream for fuel. University researchers may be good at gene cloning and producing transgenic trees, but they need to be told, by the industry, what the industry wants. Gene cloning and transgenic tree production are not trivial and must be done correctly at the beginning by having a clear goal. Industry knows what type of wood is needed, knowledge of which a molecular biologist is often lacking. On the other hand, industry may not realize the flexibility of gene manipulation. University researchers need to convey the idea to the industry that if a wood property could be genetically down-regulated it could be up-regulated as well. Mutual education between forest products industry and academia is needed to clarify uncertainties on desirable traits and perceptions of biotechnology to allow a clear identification of the realistic target traits for genetic modification. Such a clear focus would certainly help facilitate the generation of various lines of scientific evidence to support efforts on public acceptance of transgenic trees.

We have to ask the question “what real world problems can forest biotech realistically help solve”? Is solving the problem this way as environmentally, socially and economically desirable as other technologies?

We must have a clear focus on the traits needed to be engineered today to be ready for tomorrow.
Forest Biotechnology in North America
Are We Ready for a Leap in Domestication?

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What impacts will biotechnology have on North American forest ecosystems? The question is an important one, as new forest biotechnologies may soon be available for commercialization. They have the potential to result in a rapid change in the domestication of tree crops in commercial forests and to impact forests managed for other objectives. The ecological effects that could result from this transition deserve close consideration. While the scientific/social issues have been clearly defined, there is an apparent void in leadership concerning scientific research that needs filling as soon as possible.

**Limited Domestication to Date**

Let’s begin with a look at the status of North America’s commercial forests at present. The tree crops in North America’s commercial forests have undergone very little domestication in spite of 50+ years of tree improvement. This statement is true in both a relative sense compared to food crops and domesticated animals, as well as in an absolute sense.

For means of comparison, consider the human-induced genetic diversity of dogs. Unlikely as it may seem, Chihuahuas and Labradors both derive from a single sub-species of wolf (see Figure 1). All existing breeds of dogs, in fact, were domesticated from the same subspecies of wolf — illustrating the vast phenotypic differences that are possible within a single species.

**Perhaps biotechnology’s biggest impact to date has been through tree cloning.**

By comparison, the results of one generation of conventional tree improvement are small, as shown in Figure 2. Data from the first generation of improved Douglas-fir indicate that only modest domestication has been achieved.

Perhaps biotechnology’s biggest impact to date has been through tree cloning. While significant increases in tree size and uniformity have been achieved, the differences pale in significance to differentiation within dog breeds. Figure 3 illustrates these advances. Pictured on the left is a full-sib family of the slash pine x caribaea pine hybrid. At right is a clone from the same family. Note how the clones are clearly larger, straighter, and more uniform. Still, although the differences are visually striking, they are small compared to trait changes seen in either domesticated animals or plant species.

These initial results are just the beginning. Managers of North America’s commercial forests will soon have varieties available to them that are markedly...
more domesticated than even the most improved trees today. For example, we expect to have trees that are resistant to specific herbicides, are sterile, and have markedly changed chemical composition, including significantly lower amounts of lignin.

No Surprises on the Horizon

The main thesis of this paper is that forest experts have no reason to be surprised by either biological phenomena or social/political issues arising as the products of biotechnology are deployed in North American forests. In the biological arena, for instance, we know that some degree of clone x environment interaction (including environment changes caused by silvicultural practices) will exist. However, the careful and diligent testing already underway should allow us to easily cull out “dog” clones unsuitable for operational deployment.

Similarly, there is little excuse for practitioners of forest technology in general, or forest biotechnology in particular, to be broadsided by social and political issues raised by the technology they develop. Often these concerns are most clearly articulated by environmental groups (ENGOs). We typically have advance warning; issues are generally raised years, and in some cases, a decade, before technology is implemented.

Nevertheless, responsible managers of commercial forests have often been taken off guard by social and political issues. Consider what happened when the U.S. Fish and Wildlife Service listed the Northern Spotted Owl as a threatened species in 1990. The listing, or at least the magnitude of its impact on commercial forests in the Pacific Northwest, came as a surprise to much of the industry. And this occurred despite well-publicized research by the U.S. Forest Service linking spotted owl habitat to old-growth, and a clear ENGO agenda to halt old-growth logging. While the spotted owl was listed under the Endangered Species Act, its impact on the industry was largely due to it being a symbol of old-growth forests, providing significant leverage to stop old-growth logging in National Forests.

Genetic Engineering: The New “Spotted Owl”? 

Today, academic and commercial groups working on forest biotechnology in North America are faced with a similar situation. It is likely that genetic engineering technology will become a lightening rod for controversy; much like the spotted owl did 15 years ago. In fact, specific ecological issues regarding genetic engineering have already been consistently spelled out in environmental publications and websites. The following are some of the core concerns being raised surrounding

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![Fig. 2: First generation improved Douglas-fir (green) have more tall trees than wild-seed (black), but the range in tree size did not increase, indicating only a small degree of domestication.](image1)

![Fig. 3: A cloned pine hybrid (right) shows improved stem size, straightness and uniformity compared to its improved full-sib family (left).](image2)
Forest experts have no reason to be surprised by either biological phenomena or social/political issues arising as the products of biotechnology are deployed.

- To what extent will gene flow occur from GE plantations to surrounding natural stands and established public preserves? And what impact will this gene flow have on the ability of caretakers of impacted trees to meet their own management objectives, which may be very different from the plantation owners’ commercial objectives? Will the general public accept, for example, the risk of gene flow into a national park?
- What impact will sterile trees have on wildlife in managed GE plantations? The industry’s environmental research group, the National Council for Air and Stream Improvement (NCASI), has done extensive, rigorous scientific studies that document the high value of plantation forests as habitat for bird communities. Will bird populations change in sterile GE plantations?
- What effect will GE trees’ lower lignin content have on soil properties, soil organisms, and the whole decomposer pathway in general? Lignin and cellulose decompose at different rates, so some impact is plausible. Will this impact be ecologically significant or negligible?
- How stable will inserted genes be, and how robust will this stability be, in response to climatic variation and a wide range of silvicultural treatments? The question raises a related issue, namely how long GE trees should be tested before commercial deployment.

Some within the biotechnology community may not regard these as critical (or even legitimate) scientific questions. Others may have considered the issues using their scientific knowledge, and concluded via thought experiments that all effects will be minor. This could lead them to believe that the expense of experimentation, particularly in the field, is not justified. Some may argue that research expenses should be borne by those developing the technology. Others may feel that these are larger social issues, and the government should be responsible for shouldering research costs. Whichever perspective one takes regarding these questions, history has taught us that in many or most cases, genetic engineering interests will not be able to avoid addressing them.

Genetic Engineering: History Repeats

Genetic engineers have no reason to complain about being singled out or treated differently from scientists who developed other commercial forest management technologies. Even a cursory examination of the history of commercial forestry reveals the importance of experimentation to determine the long-term social and ecological effects of our practices. For example, in the past the industry has examined the effects of:

- Clearcutting and even-aged management on biodiversity in general and wildlife populations in particular;
- Road construction techniques on sediment delivery to streams;
- Riparian management on stream characteristics, including large woody debris, sediment and temperature;
- Plantation management on wetland functions;
- Acid rain on forests, and more.

For a more comprehensive list, look at the research topics studied so effectively (and extensively) by NCASI. What were the results of all these studies? In some cases, minimal effects were found, and in other cases, significant effects were determined, and management practices were changed accordingly. In many cases, the studies were very useful in developing Best Management Practices or forest practice regulations. Most importantly, in almost all cases the scientific studies played a key role in resolving social/political issues.

Time for Action

One might wonder to what extent current research is addressing these questions regarding ecological impact of genetic engineering in North American forests. To find out, I conducted an informal (and admittedly not statistically valid) survey of influential people from the forest management industry and academia. I searched for a wide variety of opinions on social/ecological questions associated with genetic engineering. The survey listed issues like the ones above regarding genetic engineering, and asked participants to what extent these questions were being addressed by current research.

Results of my survey suggest that we still have a lot of work to do in developing a more thorough...
scientific understanding to reduce ecological uncertainties. It’s true that there has been some modeling of gene flow, as well as studies of pollen movement (mostly associated with management of open pollinated seed orchards), and studies on the effects of reduced lignin on herbivores. Still, the survey revealed that if there are major scientific efforts underway to address ecological questions regarding North American forests, many prominent industry and academic leaders do not know about them.

Society thus appears to be behind the curve in addressing questions about the ecological effects of genetic engineering. Certainly, we in the industry (including Weyerhaeuser) believe that the safe and prudent utilization of genetic engineering can contribute greatly to meeting global environmental and societal goals. Yet good scientific studies are not easy to do. They will be expensive, and take a long time. And even if we start these studies today, results might not be available until about the same time that the technology will be ready for implementation.

While great progress is being made developing the scientific capacity to implement biotechnology in North America, we are lagging behind in the science required to address ecological/social issues surrounding the technology of genetic engineering. Past experience has shown that we cannot bury our heads in the sand and avoid investigating these issues. Numerous organizations could take a leadership position in this area, including the Institute for Forest Biotechnology, NCASI, the Forest Biology Research Co-op at the University of Florida, the Pew Initiative on Food and Biotechnology, or the U.S. Forest Service. The best way to do this research is in cooperation with ENGO organizations that are committed to spending as much effort helping with research as they are raising issues about the potential effects of new technology. Today, however, no one seems to be stepping up to the plate to assume leadership responsibility. Scientific leadership in this area is essential, and the time to identify suitable leaders is now.

**Endnotes**

3. Photos were taken by the author during a tour in 2001 of the clonal program at the Queensland, Australia Research Institute.
4. Robert Kellison, Institute for Forest Biotechnology, personal communication, [2004].
8. A good place to begin is www.ncasi.org.
What are the projected economic benefits and costs of forest biotechnology? How do they compare?
Forest Biotechnology from the Perspective of a Timberland Investor

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Abstract
Structural change in the forest sector has made the development and implementation of forest biotechnologies more difficult. Timberland investment as an activity distinct from the forest products industry now amounts to about $24 billion, and is growing at about 20%/year. Dis-integration of the tree-growing function from processing and marketing functions makes great financial sense, both for the forest products industry and for institutional investors. However, information flows that once took place within a single firm are now relegated to market-based transactions. Much of the anticipated gain from biotechnology is apt to come from linking specialized molecular, fiber or engineering properties of trees to specific industrial processes or specific products. These complex issues are poorly mediated by markets and the price system. Obtaining the apparent social benefits and private gains from forest biotechnology requires new ways of organizing these information flows. Some possible solutions include the pricing of R&D into such “technology products” as clonal regeneration material, enhancing forestry-based venture capital, and developing long-term growing contracts between timberland owners and manufacturing companies.

Introduction
Technical innovation has been increasing the yields of usable wood fiber from forest plantations at a rate of about 3%/year. These innovations have been developed within the context of an integrated timberland/wood processing organizational structure, a structure that has been eroding over the past two decades. A new class of owners has emerged—endowments, foundations, pension funds, banks and insurance companies (collectively, “institutions”). Integrated forest products companies have transferred perhaps 20 million acres of prime timberland to these new owners. The forest sector has always scrimped on R&D, and the new owners have shown an even lower propensity to invest in technical innovation. Given the significant economic returns that may arise from technology in general, and forest biotechnologies in particular, how can we ensure that the rate of technical progress we have seen in the past continues into the future? How can we ensure that society enjoys the benefits of technical progress in tree growing and its links to wood products and manufacturing?

Answering these questions requires digging deeper into the reasons for dis-integration of timberland. Financial and strategic considerations have led firms to sell timberland, and to organize fiber supply via markets and wood supply contracts. While disintegration has provided substantial financial benefits, it has also externalized information flows related to technical
While disintegration has provided substantial financial benefits, it has also externalized information flows related to technical innovation in timber production. Placing these information flows outside the bounds of the firm has raised the cost of technical innovation.

The economist’s theory of the firm is a useful starting point to understand these costs. This theory emphasizes the role of transactions costs in causing some activities to be amalgamated within a firm, and others to be handled through contracts and the price system. Given that timberlands have been divested, and that many of the benefits of forest biotechnology accrue to the manufacturer and not the timberland owner, the key issue is to find ways to reduce the transactions costs associated with linking timberland and manufacturing in the dis-integrated industry structure. Ideas for doing so are the focus of this paper.

We begin with some background on structural change in the forest sector. We then take a short detour back through the theory of the firm as the basis for the concluding suggestions on how we might proceed.

**Structural Change in the Forest Sector**

During the last two decades, the forest sector—particularly in the US—has dis-integrated its timberlands. The principal buyers have been institutional investors, including pension funds, endowments, foundations, insurance companies, and, increasingly, wealthy individuals.

The growth has included both private-equity vehicles and publicly traded entities. Figure 1 shows the development of these trends in the United States.

The chart breaks out private-equity investments in green (labeled as “TIMOs” or, Timberland Investment Management Organizations, the investment advisors who support institutional investments in timberland). The various public-equity entities are also included, showing the rapid ascendancy of the real estate investment trust as the preferred public-equity investment vehicle. Similar changes have occurred elsewhere in the world. For example, the large Swedish/Finnish firm StoraEnso spun out its timberland into two separate entities, Tornator in Finland and Bergvik in Sweden. These transactions, covering nearly 3 million hectares, are not included in Figure 1. Similarly, the Canadian firm

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**Figure 1. Trends in Institutional Investment in US Timberland, 1985–2003.**

Notes: MLP = master limited partnership; TREIT= timber real estate investment trust; Operating Company = “C” corporation.
TimberWest manages about $1 billion of timberland formerly held by integrated companies.

Why are integrated forest products companies selling their timberland? The reasons are many, and any one instance is likely to differ from all the others. But, several underlying factors may be identified. First, investors in most integrated forest products companies suffer two layers of taxation, one at the corporate level and a second at the personal level when profits are distributed in the form of dividends. Typically, neither the public nor private entities mentioned in Figure 1 pay taxes, with the burden being shifted directly to the investor. Removing a layer of taxes allows better returns than integrated companies can provide.

Second, publicly traded companies in the United States are required to prepare their financial statements according to US “generally accepted accounting practices” (GAAP). US GAAP consistently understates the financial performance of timberland. For example, to calculate net income, US GAAP requires companies to deduct “depletion”—the depreciation of the timberland asset—from the value of timber harvested. However, in a sustained-yield forest, there is no economic depreciation of the asset, so US GAAP understates the net income produced. Many private investors and the newer timber REITs operate on a far more favorable cash basis for reporting the ongoing returns from operations. Furthermore, US GAAP does not permit forest products companies to increase the value of the timberland on their books as the trees grow. Private investors are able to “mark to market” the value of their timberland as the trees increase in value. Interestingly, some countries—Australia and New Zealand are two examples—require firms to revalue their forests each year, and to put this value on their balance sheets. The proposed International Accounting Standards also require this practice for forestry accounts. US GAAP will soon be the anomaly for timberland return reporting, but there is no sign of change.

Finally, while there are notable exceptions, integrated forest products companies have generally not provided good returns for their investors. There are many explanations for the consistently poor returns, but some analysts have suggested that the reason lies in using strong returns from timberland to subsidize poor returns from operating facilities. As a consequence, Wall Street has pressed firms to sell their timberland and use the proceeds to pay down debt, return capital to shareholders, or to make accretive acquisitions.

These financial factors are likely to remain important for the foreseeable future, so we can expect to see integrated firms shed more timberland.

While dis-integration of timberland makes a great deal of financial sense, particularly in the short term, it does raise problems for the implementation of forest biotechnology. Specifically, companies that no longer own timberland are unlikely to sponsor research on forest biotechnology, either within their own firm or extramurally. The new institutional owners have shown an even lower propensity to fund forestry R&D than have traditional forest products companies. For example, to the best of my knowledge, Hancock Timber Resource Group is the only private timberland investment advisor that is a member of the various regional tree-breeding research cooperatives. Firms that do not sponsor R&D are unlikely to have in place adequate technical resources to be sophisticated consumers of R&D. The lack of “technology receptors” among the new forest owners will impede technology transfer and will slow the diffusion of technical innovation.

The problems are compounded because much forest biotechnology focuses on improving wood qualities related to specific products or manufacturing processes. Lignin modification is a good example. Such traits may be valuable for manufacturers, but they confer no particular
advantage to forestland owners unless markets can reliably deliver higher prices for such higher-valued trees. Genetic modifications related to almost any attribute of the molecular or fiber characteristics of wood fall into the same category.

A Digression on the Nature of the Firm

The Nobel-prize winning economist Ronald Coase wrote an article on ‘A Digression on the Nature of the Firm’ in 1937. He pondered why economic activities coalesce into firms, or, as he put it “…like lumps of butter coagulating in a pail of buttermilk.” Economists, of course, generally argue that markets are the best systems for coordinating productive activities. If markets work so well, why do firms exist at all? Why aren’t we all independent contractors with constantly shifting business relationships, each one of which is governed by separate prices and terms? Coase answered the question on the basis of transactions costs. That is, it is less costly to pull together related production activities into a single organization (“the firm”) guided not by internal prices, but rather by the “entrepreneur co-ordinator”. The cost of organizing a separate contract for each exchange activity arising within the firm exceeds the efficiency gains associated with using the price system to govern these relationships. Firms can be expected to extend their boundaries until the balance of the equation tips the other way, and the efficiencies of specialized production make outsourcing cheaper than internal co-ordination.

Integrated forest products companies have found ways to coordinate timber supply through the price system without having to own the land itself. In much of the US, timber markets are deep and active. In instances where they are not, companies can still divest timberland if they retain access to the wood through wood supply agreements—increasingly prominent in timberland divestitures. In short, changes in transportation infrastructure and information technology mean that the transactions costs of organizing timber supply through markets have fallen, and it is no longer necessary to keep the forestry function within the firm. But, as forest ownership has been outsourced, firms have lost the capacity to coordinate internally the integration of tree growing with wood products manufacturing.

Practical Implications for Forest Biotechnology

Traditionally forest biotechnologies have been organized via entrepreneurial coordination within individual firms. As the firms dis-integrate their timberland, new modes of coordinating the production of forest biotechnologies must be developed. These will logically rely on the price system and contracts rather than the traditional “command and control” methods of the past.

Within this general premise, three specific approaches suggest themselves:

i. Sell forestland owners technology products, not R&D projects.

ii. Establish forestry venture capital activities.

iii. Establish growing contracts between forestland owners and manufacturing companies.

Let’s examine each of these in more detail.

Begin with two assumptions: 1. technical innovation pays acceptable risk-adjusted returns, and 2. new institutional timberland owners are structurally discouraged from investing in R&D as a result of not owning integrated manufacturing facilities. Given these assumptions, one can imagine the emergence of a group of specialized forestry technology companies providing these innovations on the basis of either charging fees for services or by selling products with the technology embedded in them. We see the emergence of both models. In the former case, Westvaco spun out much of their forest management technology into the Forest Technology
Group. International Paper offers similar services via their subsidiary Sustainable Forest Technologies. Specialty aspects of forest management planning—traditional forest inventory, remote sensing, geographic information systems, and computer-based forest planning—have long operated on the fee-for-service model, with the R&D expenditures coming outside the forest products industry itself. CellFor, the private forest biotechnology company formed by combining Pacific Forest Biotechnologies and Silvagen, seeks to sell forest biotechnology innovation embedded in the planting material.

One can imagine the logical evolution of this business model, where a specialized firm takes on the full-cycle task of forest regeneration:

- identifying the most appropriate genotypes for a particular site and owner,
- arranging for the optimal level and kind of site preparation,
- hiring contractors to plant the best regeneration material for that particular site,
- handling post-planting herbicide and fertilizer treatments, and
- being paid at least in part on, say, the height of trees at age 5.

Such a model re-integrates one of the most important aspects of plantation forestry—regeneration—into a firm that can take a comprehensive, coherent view, and provides performance-based incentives for good outcomes. Contracts and the price system are used where they make the most sense, but entrepreneurial co-ordination is used where the site conditions and other details increase the transactions costs of market-based mediation.

This model would appear to work well where there is a stock of technical innovation that awaits application, but it begs the question of where the capital investment will come from to finance the innovation in the first place. Traditionally, integrated companies have diverted some fraction of the profits from forestland ownership to support R&D. Institutional owners are generally not similarly inclined, and this is logical: they are investing in timberland, not R&D (analogously, most do not want to own “higher and better use” land because that is speculation in rural real estate and not timberland investment). Conceptualizing timberland investment this way suggests a solution: create a new capital investment opportunity in forest-based R&D, or, said another way, forestry venture capital. Indeed, it was an agricultural venture-capital firm, Agricultural Technology Partnerships, which catalyzed the creation of CellFor. If the public sector is backing out of forestry R&D, and if integrated companies no longer subsidize this activity, there is now room for the private sector to invest profitably.

Finally, recall that the separation of timberlands and processing facilities demands that the interactions between these two activities are handled through the contracts and the price system. Following this logic suggests a way forward: processing firms can contract with timber growers to produce trees with desirable wood qualities which are poorly priced in markets. Already timber markets distinguish between the sizes of the trees and their straightness, and, to some degree, whether or not the trees have been pruned. It is a small step to have the market distinguish among, for example, lignin characteristics and levels. Until such markets exist, however, it would be exceedingly risky for a non-integrated forest grower to plant, at high cost, such trees in the hopes that the market would, some day, reward her for her prescient decision. Companies who want this kind of material can take some of the risk out of the transaction by agreeing to buy such material at an agreed-upon premium price. The price logically covers the added cost to the grower, and splits some of the full-system gains.
Separation of timberland from processing facilities clearly creates financial gains for both the formerly integrated forest products companies and the new institutional owners. Offsetting these gains are losses associated with the reduced ability to integrate technical innovations in the forests with those in manufacturing processes and products. New methods of operation—R&D embodied in, and sold as a part of, technology services and products; forestry venture capital; and new kinds of contractual relations between forest growers and timber processors—will be required to continue to achieve these gains.
Forest Biotechnology Deliverables

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Abstract

Developments and applications of forest biotechnology are rapidly expanding. Aspects of forest biotechnology are becoming both more complex and more accessible due to progress in molecular genetics and information technology. Despite their many similarities, there are some fundamental differences between the potential applications of biotechnology in forestry and agriculture. These stem from the inherent contradictions in the many cultural and utilitarian roles forests play, and the relatively recent domestication of forest trees. We propose five major, but partially overlapping categories of forest biotechnological tools: (1) molecular markers, (2) propagation, (3) genomics, (4) marker-aided selection and breeding, and (5) genetic modification. These tools apply differently to forest practitioners and to researchers. Deliverables therefore vary with respect to their scopes and scales of application, and development status. We describe the nature and status of these tools and their deliverables in research and practice, their relevance, feasibility and operational aspects in forestry.

Introduction

Forest biotechnology is still in its early stages, and can benefit from the experience of agriculture in addressing technical and societal issues. Trees and agricultural crops share some similarities with respect to their utilitarian roles in human society and culture, but they differ in their history of domestication and underlying cultural paradigms (Owusu 1999; Pew Initiative 2001). Crop species have been altered to such an extent to suit humans that they usually bear little resemblance to their wild progenitors (Hancock and Hokanson 2001; FAO 2002). Unlike some forestry methods, agricultural practices are generally not viewed as ecologically detrimental. Forests have a complex and dichotomous role in human cultures. They provide important products like fiber and food, and also less tangible values like wilderness, habitat and ecosystem functions. Sustainably accommodating these two sets of values may be impossible in some instances. Dedicated areas may be allotted for exclusive wilderness and/or non-timber forest products, and for intensive management (Binkley 1997; Sedjo 2001).

Over the past two decades, biotechnology has been recognized as one potential means of enabling such a compromise (Haines 1994; Sedjo 1999). Global fiber demand will continue to rise, while availability of inexpensive, high-quality old-growth forests is declining (Fenning and Gershenzon 2002; Gartland et al. 2002). Fiber production on intensively managed, short rotation high-yield plantations is one option to meet this demand using a smaller land base.

Forest biotechnology deliverables may be categorized into those which currently benefit forest practitioners and those which provide important benefits for research, but are not yet transferable to the field at an operational scale. The range of tools provided by forest biotechnology can be subdivided into five major types, which overlap due to their stepwise development, but represent different ultimate objectives and deliverables. These tools are: (1) molecular markers, (2) asexual propagation (i.e., cloning), (3) genomics, (4) marker-aided selection (MAS)

The use of the whole or targeted portions of organisms to provide quantitative information and/or desired products, including the isolation and/or manipulation of specific genetic components of that organism (El-Kassaby 2003). This definition was developed to include both conventional breeding and more recent technologies.
and breeding (MAB) and (5) genetic modification. Only the last involves genetic manipulation of living trees, but some marker development and creation of cDNA libraries for genomics may involve transformation of bacteria, plasmids or tissues in the lab. Each tool has unique potential applications, risks and benefits (Table 1). Some tools function at the subcellular to whole-plant levels, while others are implemented across the landscape (Table 2). Agricultural biotechnology has seen rapid development and deployment of such innovations (Pew Initiative 2003; Figure 1), where many tools have moved from research into practice. Forest biotechnology has started shifting its focus towards applied topics and away from solely exploratory issues (Gupta 1999; Mifflin 2000). Genetic and biochemical distinctions between annual plants and woody perennials will form the basis of future research directions for forestry deliverables (Table 2; Walter et al. 1998; Rottmann et al. 2000; Lev-Yadun and Sederoff 2000; Hershbach and Kopriva 2002; Wang et al. 2003).

Table 1. Current applications and projected future importance and trends of forest tree biotechnology in developed nations (scale of 0-3: 0 = nil, 3 = common; modified from El-Kassaby 2003).

<table>
<thead>
<tr>
<th>Broad Technologies</th>
<th>Components</th>
<th>Current Application</th>
<th>Trends and Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioinformatics</td>
<td>Large databases</td>
<td>3</td>
<td>The storage, retrieval, analysis, and interpretation of large amounts of genetic data transcend boundaries of all broad biotechnologies. Capability and application range will continue to increase dramatically. Data mining and integrated analyses and syntheses will greatly increase power to detect genes and understand their functions. Databases co-ordination, accessibility and transparency are essential. Bioinformatics research requires resource-intensive, multidisciplinary teamwork, naturally leading towards more international cooperation over a range of study scales and systems. Opportunities are opening up for involvement of developing countries.</td>
</tr>
<tr>
<td></td>
<td>Targeted DNA Sequencing</td>
<td>3</td>
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<td></td>
<td>Proteomics</td>
<td>2</td>
<td></td>
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<tr>
<td></td>
<td>Mapping of Genes &amp; Markers</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Microarrays</td>
<td>2</td>
<td></td>
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<tr>
<td></td>
<td>Quantitative Traits</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Integrated Applications</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Broad Technologies</td>
<td>Components</td>
<td>Current Application</td>
<td>Trends and Deliverables</td>
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<td>-------------------------</td>
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</tr>
<tr>
<td>Diversity Measurement</td>
<td>mtDNA, cpDNA</td>
<td>2</td>
<td>The use of molecular markers for studying population genetics of natural and planted forest tree populations has enabled unprecedented expansion. Applications include measuring genetic diversity, comparisons among taxa and populations, historical reconstruction and prediction of species’ range shifts, gene flow, assessment of natural and artificial (e.g., seed orchard) population mating systems, introgression and hybridization, and impacts of disturbance and management. Markers have facilitated genomic and QTL mapping. Development costs are decreasing and applications are expanding.</td>
</tr>
<tr>
<td></td>
<td>RAPD, AFLP, RFLP</td>
<td>3</td>
<td></td>
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<tr>
<td></td>
<td>SSR, STS</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SNP, ESTP</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Gene Discovery</td>
<td>Phenotypic Traits</td>
<td>3</td>
<td>Phenotypic and quantitative trait measurements drive conventional tree breeding, resulting in significant gains in many species worldwide.</td>
</tr>
<tr>
<td>QTL Mapping</td>
<td></td>
<td>3</td>
<td>QTLs will increase in utility, particularly for traits controlled by few major genes which are difficult to phenotypically assay (e.g., wood properties, disease and insect resistance).</td>
</tr>
<tr>
<td>Genome &amp; EST Sequencing</td>
<td></td>
<td>2</td>
<td>Massive, redundant conifer genomes restrict sequencing to specific regions. EST sequencing for commercially important species is progressing. Economically and ecologically important angiosperms will be completely sequenced. International collaboration is important for species with extensive ranges.</td>
</tr>
<tr>
<td>Microarrays</td>
<td></td>
<td>2</td>
<td>Microarrays are being completed for gene discovery and understanding gene function for growth and yield, wood quality and adaptive attributes; more reliable oligo-based will likely replace cheaper clone-based arrays.</td>
</tr>
<tr>
<td>Proteomics</td>
<td></td>
<td>2</td>
<td>Proteomics aims to elucidate protein variation beyond simple transcription, including expression, interactions and post-translational modification.</td>
</tr>
<tr>
<td>Metabolomics</td>
<td></td>
<td>1</td>
<td>Still in the initial stages, metabolomics assesses the presence/absence of non-protein structural precursors of essential components in biochemical pathways.</td>
</tr>
<tr>
<td>Molecular Genetic</td>
<td>Gene Insertion/</td>
<td>2</td>
<td>This technique could enable gene transfer in cases where it is not feasible via conventional breeding. Transformation is widely used in agriculture, but is new to forestry and has engendered major public contention and strict biosecurity protocols for testing and deployment, especially regarding potential gene escape into wild populations. This technique could potentially improve important qualitative, quantitative, economic and adaptive attributes.</td>
</tr>
<tr>
<td>Modification</td>
<td>Sequence Modification</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gene Targeting/</td>
<td>2</td>
<td>Gene knockouts will expand based on the results of microarray and proteomic analyses. There is a broad spectrum of potential functional genomics applications and associated ethical issues also pertinent to gene insertion.</td>
</tr>
<tr>
<td></td>
<td>Knockout</td>
<td></td>
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</tbody>
</table>
### Forest biotechnology challenges

The rapid increase in forest biotechnology applications is reflected in the rapidly growing work force, number of labs, related businesses and capital investment (Devlin 2003; Industry Canada 2004). Developed and developing nations have differing priorities, resources and acceptance levels for biotechnology (FAO 2004). There has been rapid progress throughout Asia and in some South American countries in adapting biotechnology for direct public benefit. Examples include measures to reduce use of and exposure to harmful herbicides and pesticides, to increase crop disease resistance, environmental stress tolerance and yields, and enhance food security (Gartland et al. 2002; Pew Initiative 2002; FAO 2004). Some countries, like China and India, feature publicly funded research initiatives, while others (Malaysia, Argentina, Chile) conduct research solely or in partnership with private companies, which may be domestic or foreign (Owusu 1999). Administrative and logistical support to developing nations in forest biotechnology has often come in the form of agencies and organizations such as CAMCORE, a partnership between countries from Central and South America and the U.S.A. (Devlin 2003). It is not possible to generalize regarding directions for forest biotechnology in developing countries. Each nation will choose to pursue a program according to resource availability and domestic priorities (Pew Initiative 2001).

Obtaining information on privately-funded biotechnology is often difficult due to intellectual property, confidentiality and patent restrictions (Owusu 1999; Devlin 2003). In all developed nations except the U.S.A., government funds nearly all of the extremely expensive baseline research and infrastructure. Academia provides support via training personnel and facilities. Applied research and development often include collaborations with private partners. While collaborative research can provide lucrative opportunities, proprietary tech-

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### Table: Broad Technologies

<table>
<thead>
<tr>
<th>Broad Technologies</th>
<th>Components</th>
<th>Current Application</th>
<th>Trends and Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Verification</td>
<td>Pedigree Verification</td>
<td>3</td>
<td>Developing larger-scale, lower cost application platforms will increase accessibility by genetic improvement programmes, expanding the prevalent uses: pedigree verification and verifying clonal identities. Other potential applications include evaluating seed orchard management efficacy and growth and yield determination of resulting crops.</td>
</tr>
<tr>
<td>Quality Control/Quality Assurance</td>
<td>PCR-based product description systems, commonly used in food manufacturing, will increase support for research and application of automated systems. Gene markers will be used to check process efficiency during mass production of clonal seedlings.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cloning</td>
<td>Organogenesis</td>
<td>1</td>
<td>Most of the shortcomings of organogenesis can be overcome using somatic embryogenesis, but methodology and success are genotype- and species-specific. These methods are currently in production. Cloning will be a significant element in high yield plantation forestry.</td>
</tr>
<tr>
<td>Cloning</td>
<td>Somatic Embryogenesis</td>
<td>1</td>
<td>Measuring and monitoring components of clonal production will increasingly employ physical, chemical and molecular markers to detect specific biological processes, e.g., expression-tagged genetic markers.</td>
</tr>
<tr>
<td>Biosensing</td>
<td>Simple Biosensors</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

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Forestry requires long-term rotations, during which environmental conditions change temporally and spatially.
Table 2. Anticipated contribution to and scale of impact of each broad area of biotechnology on elements of forest populations (modified from El-Kassaby 2003).

<table>
<thead>
<tr>
<th>Applicable Forestry component</th>
<th>Spatial Scale</th>
<th>Development Elements Relevant to Biotechnology</th>
<th>Broad Technologies</th>
<th>Molecular Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Populations</td>
<td>tree – population</td>
<td>Genetic Resources Characterization</td>
<td>Bioinformatics</td>
<td>Diversity Measurement</td>
</tr>
<tr>
<td></td>
<td>population</td>
<td>Mating System/Gene Flow</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>population – landscape</td>
<td>Conserving Diversity</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>population – landscape</td>
<td>Silviculturally Impact Assessment</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Breeding Populations</td>
<td>tree</td>
<td>Selection</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>tree – population</td>
<td>Mating Designs</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>tree</td>
<td>Progeny Testing</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>tree</td>
<td>Attribute Assessments</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>population</td>
<td>Diversity Management</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Production Populations</td>
<td>population</td>
<td>Mating System</td>
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tology creates obstacles for other researchers, who may have to utilize more costly or inefficient techniques to avoid violating patents, or become partners with the patent-holder. There is currently a vigorous debate regarding the impacts of proprietary agreements and potential researcher bias (Pew Initiative 2002). Land and resource ownership (i.e. public or private) also plays a key role in reaching appropriate decisions.

While the biological and societal constraints on forest biotechnology may be distinct, they cannot be realistically isolated in policy and practice. Trees have many important biological and management differences from annual agricultural crops which would affect their suitability and cost-effectiveness for biotechnology. Forestry requires long-term rotations, during which environmental conditions change temporally and spatially. Trees are generally obligate outcrossers, susceptible to inbreeding depression, and thus maintain extremely high genetic diversity within and among populations to adapt to environmental fluctuations and contingencies. Many important traits vary among different environments (genotype-by-environment interaction: Zobel and Talbert 1984). The genetic and phenotypic resemblance of improved trees to their wild congeners allows frequent gene flow via exchange with nearby wild gene pools (Walter et al. 1998; Mann and Plummer 2002b). Trees have extended juvenile phase and may require decades to sexually mature, so breeding and selection is very slow. Pedigrees only exist for the most advanced breeding programs which are in the third generation. Most economically useful traits are evident only upon maturity and cannot be accurately predicted from juve-
 Nile characters (Strauss et al. 1992; Moffatt 1996). Multiple desirable traits may be negatively or unpredictably correlated, influenced by epistasis, or result from unknown gene action, so progress using traditional breeding and selection has been difficult, slow or impossible for some traits (Strauss et al. 1992; Williams and Neale 1992).

Many factors must be carefully evaluated by regulatory authorities prior to determining whether biotechnological tools and products can be approved for testing, and at what scale (Government of Canada 1985; Mullin and Bertrand 1998; Pew Initiative 2001). Gene flow is of paramount concern. It may occur via pollen, seed or vegetative propagule spread. The novel trait could be transferred or altered through escape, expression changes, hybridization, introgression by horizontal or vertical gene transfer, or increased weediness (Strauss et al. 1995). The scientific community acknowledges that such escapes cannot be completely prevented (DiFazio et al. 1999; Johnson and Kirby 2001), so studies are an essential component of regulatory permitting to evaluate any impacts on fitness of the organism and the environment associated with transfer or spread of modified traits or gene sequences (Crawley et al. 2001; Heron and Kough 2001; Hay et al. 2002). Adding reporter genes with visible products would aid in monitoring and controlling spread of novel germplasm. The public is extremely concerned about potential risks associated with scaling up and unconfined operational release. Tests are still being conducted at an extremely controlled, homogeneous, small scale. To accurately predict and mitigate any potential impacts and to accurately assess risk over the long term, tests must simulate environmental conditions, including variability, expected upon release as closely as possible (James et al. 1998; Mullin and Bertrand 1998; Hay et al. 2002; Pilate et al. 2002). It is widely agreed that each plant and trait must be assessed on a case-by-case basis (Government of Canada 1985; Heron and Kough 2001; FAO 2002).

Certification has emerged as an influential tool for consumers to exercise their opinions regarding forest management through purchasing decisions. There are many agencies that certify forests, processing facilities and forest products, all with different criteria, membership and standards. Few forest certification organizations have explicitly addressed the issue of biotechnology. The largest independent agency, the Forest Stewardship Council, has explicitly excluded genetic modification from certification (FSC 1996). Forest plantations, including those containing clones, have been certified by FSC and other groups. Pulp mills using biotechnology to produce products or treat waste have been process certified (e.g., ISO 14001). Benefits include the potential to reduce environmentally harmful pulp processing chemicals in wood with modified lignin or cellulose, or reducing the need for toxic chemicals by using genetically modified enzymes for processing (Baucher et al. 1996; Pilate et al. 2002; Huntley et al. 2003). Most people are unaware of the increasing applications of biotechnology in materials processing, but appear to be more concerned when the products are to be ingested as food; i.e., not as medicine (e.g., insulin), trace additives (e.g., flavour or colours) or used externally (e.g., synthetic materials or colouring) (Gartland et al. 2002). There is considerable consternation over the potential for release of transgenic trees into the environment, clonal plantations, and other forestry activities perceived as “unnatural”, although proponents argue that the nature of the trait or practice should be regulated and not the technology (e.g., Strauss et al. 2001). Public acceptance of technologies and practices is strongly influenced by the perception of whether it serves the public good, or if benefits will primarily accrue to private companies (Pew Initiative 2001; FAO 2002, 2004).
Deliverables for practitioners: current status and trends

Propagation
The most accessible biotechnology deliverables are used in vegetative propagation. Plantations increasingly rely on clonal forestry and family forestry. Implementing intensive management, which may include cloning elite genotypes to maximize growth and yield, is economically and ecologically attractive: it may reduce the ecological footprint of forest management, while providing larger and more rapid returns on a traditionally low-margin, long-term investment (Sedjo 2001; Fenning and Gershenzon 2002). Returns are higher since additive and epistatic genetic gains can be captured using elite lines, resulting in substantially higher performance than seedlings bred in seed orchards, which can only exploit part of the total genetic variation (Johnson et al. 2000). Clonal uniformity reduces net costs associated with forest planning, harvesting, and product processing (Grossnickle and Sutton 1999). Phenotypes with traits that have low or complex heritability due to linkage equilibrium or multigenic control, such as disease or pest resistance, can also be replicated (Strauss et al. 1992; Williams and Neale 1992). Although it is much more expensive to use clonal than zygotic seedlings, the cost is very small relative to the total cost over a rotation, and could be easily offset by the accelerated return (Haines 1994; Sedjo 1999).

The major types of clonal propagation technology are organogenesis and embryogenesis. Both can produce many copies of a single genotype. Somatic embryogenesis can produce infinite copies, which may be stored at very low temperatures (cryopreserved) indefinitely with no detrimental effects (Grossnickle and Sutton 1999). Success of most vegetative propagation techniques varies, depending on the tissue type, developmental stage, species, genotype, environment, and culture technique (Giri et al. 2004). Conifers are more recalcitrant than angiosperms, but a few of the most economically important species have been successfully cloned (Grossnickle and Sutton 1999; Peña and Seguin 2001; Sutton et al. 2004).

Molecular markers
Prior to the development of genetic markers, phenotypic mutants were used to study a limited range of genetic topics. Protein and metabolic markers followed (e.g., terpenes, isozymes), allowing researchers to assay compounds which were indirectly related to the actual genetic variability within populations and species. DNA characters can now be directly measured due to the development of the polymerase chain reaction (PCR). Population and molecular genetics now has a virtually unlimited set of tools which can be combined to investigate most genetic questions. Baseline population genetic information, such as genetic diversity, mating system and population dynamics, is now available for hundreds of species of forest trees, allowing researchers to infer evolutionary relationships and historical events.

Operational applications of markers include quantifying genetic diversity and impacts of disturbances at various spatial and temporal scales. Genetic consequences of various land use and forestry practices can be measured so benchmarks can be included in sustainable forest management (SFM) guidelines. Quantitative relationships between molecular marker data and phenotypic and geoclimatic variables, patterns of genetic variation and degrees of adaptability are incorporated into forest genetic resources management. Best practices are reevaluated periodically using geneecological studies. Seed production, germplasm transfer and silviculture regulations all reflect these results (Yanchuk 2001). Tree breeding programs routinely use markers to character-

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1 Deploying copies of the best (elite) individuals for maximum genetic gain.
2 Deploying copies of progeny from a full-sib “family” for higher diversity; genetic gains of progeny are the averages of the parents.
3 Regenerating copies of an individual from selected tissues, including rooted cuttings, grafting and tissue culture.
4 Propagation and growth of asexually generated embryos.
ize selected individuals and their offspring, examine pedigree structure, assign paternity, measure inbreeding depression, and for quality control in breeding and management practices, progeny identification and to measure pollen contamination (reviewed in El-Kassaby 2000).

**Deliverables for researchers: current status and trends**

Other deliverables of forest biotechnology are more academic in nature or scale, and are currently in the development and testing stages. Drawing on the experience of agriculture, researchers anticipate great potential for marker-aided selection, genomics and genetic transformation using forest trees. While these categories are not mutually exclusive, they represent different facets of forest biotechnology.

**Propagation**

The most obvious application of propagation in forest biotechnology research is its utility in genetic engineering. Cloning as an “enabling technology” provides the only viable method to propagate transformed genotypes for research and testing (Walter et al. 1998). Research on organogenesis and embryogenesis of commercially important trees is rapidly progressing due to increasing interest in clonal forestry. To date, few species have been successfully cloned to create stable, indefinitely replicating clonal lines (Giri et al. 2004). Although conifers are more difficult to clone than angiosperms, species including spruces, several commercially important pines, larches, sequoia and Douglas-fir have been successfully micropropagated.

Advanced research in biochemical and regulatory pathways controlling the steps in propagation are needed to enable researchers and practitioners to streamline the cloning process and more effectively troubleshoot. Overcoming current problems such as: 1) cloning recalcitrant species and individuals would allow valuable genotypes to be more easily propagated, 2) increasing induction rate to allow capturing of greater genotypes and the incorporation of cloning into breeding and testing programs, 3) improving conversion rates during the cloning and seedling production phases would improve the process efficiency, 4) the development of methods that industrialize the system to increase efficiencies and cut costs, and 5) understanding the biological factors at work during cryopreservation would also be an important development for germplasm ex situ conservation. Unique genotypes and tissues, rare seeds and ecotypes, and seed which cannot germinate under current natural conditions can be stored indefinitely, or until reintroduction into their natural habitat is feasible (Mann and Plummer 2002a). To this end, research has been ongoing into in vitro propagation and cryopreservation of disease-resistant chestnut and elm.

Much of the research and development in this field is conducted by private companies, so some equipment, methodology, and genotypes are proprietary. The results of research by government and academia are available in the peer-reviewed literature. Public agencies lag behind private companies in somatic embryogenesis of commercially important conifer species (Grossnickle and Sutton 1999; Pew Initiative 2002).

**Molecular Markers**

There are a plethora of molecular markers that range in applicability and costs (Table 2; Ritland and Ritland 2000). Evaluating a larger number of loci provides a more accurate estimate of the true patterns of genetic variability in an individual’s genome. Assessing entire populations documents the variability within and among populations and species. Most markers identify specific or random DNA segments, facilitated by enzymes which target DNA sequences. These markers are selectively neutral, providing a random snapshot of genetic variability
throughout the genome, and are used in a wide range of studies. Markers that denote adaptive or selected traits, like quantitative trait loci (QTL), are more difficult to detect and interpret. They require considerable preliminary work to develop a robust framework to interpret results, such as a breeding pedigree and/or comprehensive genome map of markers and putative genes on linkage groups (Strauss et al. 1992; Johnson et al. 2000).

Despite the added costs, non-neutral markers like QTL may be more informative since neutral markers are generally uncorrelated with traits of interest and are thus not directly useful for breeding and selection (Williams and Neale 1992; Walter et al. 1998; Yanchuk 2001). Genetic markers linked to traits have been identified, including components of stress (e.g., cold, drought, salinity) tolerance (Hershbach and Kopriva 2002), herbicide resistance (Meilan et al. 2002; Wang et al. 2003), lignin and cellulose quality (Hu et al. 1999; Pilate et al. 2002), and their various biosynthetic pathways (Gupta 1999; Kirst et al. 2003), but none are currently used for selection or breeding.

Genomics

Genomics is a relatively new field, integrating molecular structure, pathways and functions, evolutionary relationships, high-throughput equipment and biostatistical analysis (Krutovskii and Neale 2001). Most genomics research is conducted by government and academia, focusing on sequencing and gene discovery (FAO 2004). Associated new technologies like microarray analysis⁶ to discover groups of genes and their regulatory relationships, bioinformatics⁷, proteomics⁸ and metabolomics⁹ all provide support to understand complex genetic control of organismic biochemistry. Developmental changes and stress responses may be too subtle or complex to assess using simple markers, mutants or biochemical assays. Geneticists predict that assembling a composite picture of an organism's entire genome, either by sequencing or via a large number of expressed sequence tags (ESTs), will spark new developments in gene discovery and evolutionary genetics.

To date, the greatest practical contribution of QTL mapping to forestry is in clarifying the genetic architecture of quantitative traits through identifying genes associated with specific biological functions (association mapping: Krutovskii and Neale 2001). Functional genomics is expected to rapidly progress based on recent advances in DNA sequencing, identification of single nucleotide polymorphisms (SNPs) and quantitative trait nucleotides (QTNs) which pin-point genes controlling phenotypic traits (candidate genes).

One aim of genomics is to convey a detailed understanding of the locations, functions, interactions and evolutionary relationships among genes. The entire process is extremely resource- and labour-intensive, requiring very large capital outlays for startup, chemicals and equipment, and highly skilled support staff, so most activity is confined to developed nations. The first step involves constructing detailed genomic maps, using molecular markers to locate genes linked to or controlling traits of interest (Moffatt 1996; Gupta 1999). New high-throughput automated technologies have been instrumental in sequencing genomes and locating targeted regions for many species. Conifers have extremely large, redundant genomes containing lengthy non-coding segments or non-functional regions. These attributes effec-

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⁶ Systems approach for visually assaying simultaneous regulation of many interacting genes, based on “chip” technology
⁷ Simultaneous statistical analysis of large arrays of genetic data
⁸ Systems approach to evaluating an organism’s total protein structure and processes, involving 2-D electrophoresis
⁹ Systems approach for evaluating an organism’s metabolic processes
tively preclude complete sequencing of conifers at present, and researchers are focusing instead on functional regions using microarrays and cDNA libraries (Walter et al. 1998; Lev-Yadun and Sederoff 2000). Advances using model species such as Arabidopsis, maize and rice have greatly accelerated developments in sequencing the entire poplar genome, gene discovery and determining synteny among taxa (Mifflin 2000; Kirst et al. 2003). Key research areas include identifying genes and pathways involved in insect and disease responses, stress tolerance, and wood quality traits (Wang et al. 2003).

Marker-aided selection (MAS and breeding (MAB))

Using molecular markers linked to or within loci controlling traits is a recent development in agriculture, although it has been long anticipated (Gupta 1999; Mifflin 2000; Giri et al. 2004). The long life span and breeding cycle of trees is the key target for MAS/MAB: researchers anticipate shortening breeding cycles by decades as selections can be made on embryos or seedlings (Campbell et al. 2003). Many of the requirements and caveats which apply to genomics are also relevant for MAB and MAS, since they rely on overlapping technologies. In most cases, QTL for the traits of interest must be identified in parents and tested and verified in offspring. Further, each QTL must be verified and validated for different crosses, lines, environments and time periods to assay their stability (Strauss et al. 1992). Statistical power to detect QTL depend on the size of the progeny array (and clonal replicates), the number of genes controlling each trait, the magnitude of effect of each QTL, genetic architecture of the trait (e.g., genotype-by-environment interaction, heritability, proportion of additive variance), breeding strategy and analytical design (Williams and Neale 1992). Correlations between phenotype and genotype at each QTL controlling each selected trait must be tested (Krutovskii and Neale 2001). The strategy and pedigree analysis are critical, especially with outbred organisms like forest trees. Molecular markers also play an important role, since each marker has different strengths and weaknesses depending on the breeding design and segregation pattern for traits of interest and candidate genes (Sewell and Neale 2000). Most MAS techniques involve constructing a genomic linkage map to visualize QTL positions on linkage groups, and test for linkage disequilibrium, pleiotropy and co-location (Beavis 1998). Candidate genes currently holding the most promise for improvement via MAB in forest trees include those on lignin synthetic pathways, various mechanisms of disease- and pest-resistance, phytohormone-based herbicide tolerance and stress tolerance pathways (Hu et al. 1999; Mann and Plummer 2002b; Campbell et al. 2003). Other important potential uses for MAS include genotyping for quality assurance, such as pedigree and trait confirmation (Tables 1 and 2). Modeling studies show the relative efficiency of MAS depends to a large extent on the number of genes influencing the trait, their heritability and method of gene action, as well as numbers of progeny available for testing (Williams and Neale 1992; Johnson et al. 2000; Wilcox et al. 2001). Studies on QTL for forest trees lag far behind other model organisms due to the challenges imparted by both conifer biology and the (MAS/MAB) system, although developments in new marker technology show promise (see Genomics section) (Sewell and Neale 2000).

Necessary prerequisites to MAS/MAB are construction and verification of detailed genetic maps including QTL. For MAS to be practical, maps should be very dense across the entire genome using the most informative markers possible with known inheritance. This has so far not been feasible for forest trees due to their heterozygous nature and susceptibility to inbreeding.
depression. Unlike forestry, agriculture can capitalize on inbred homozygous (isogenic) lines to directly pinpoint segregating loci. Controlled crosses using hundreds or thousands of progeny, which are necessary for adequate statistical power, are generally not available in contemporary conifer breeding programs (Strauss et al. 1992; Johnson et al. 2000; Giri et al. 2004), but can be overcome by careful experimental design (Williams and Neale 1992). Analyses must be replicated for each line to test stability and consistency of QTL across genetic and environmental backgrounds over time. The added field and laboratory costs are such that the additional initial outlay is not yet considered justified by tree breeders, given the low precision of breeding and selection for marker-based traits at present. Genetic gains from MAS will be largest in traits with low heritability controlled by many loci (Lande and Thompson 1990), which are precisely those traits most inefficient to conventionally breed. Such traits may be more efficiently targeted via MAS/MAB by subdivision into fewer traits with higher heritability (Sewell and Neale 2000).

Genetic modification

Despite the extensive public and media attention this technology has garnered, genetic modification of forest trees, pioneered over 15 years ago (Fillatti et al. 1987) remains the purview of research and is not operational. Fruit trees, which have been the subject of considerable research, will not be included in this discussion since they do not generally fit into a forest management framework. The necessity of appropriate testing, both in the lab and confined controlled field tests, contribute to the prolonged regulatory process of genetically modified trees, since desirable characteristics often appear in mature or large individuals (McLean and Charest 2000; Heron and Kough 2001; Mann and Plummer 2002b). Performance and environmental tests are: parameters including stability, expression levels, specificity of expression based on tissue, environment, or development, and environmental persistence and impacts of modified sequences including genes, promoters, and flanking regions (Hu et al. 1999; Lindroth et al. 1999; Lev-Yadun and Sederoff 2000; Hershbach and Kopriva 2002). Angiosperm tree research, particularly in poplars and eucalypts, is further advanced than conifers, but some pine, larch and spruce species of commercial interest have been intensively studied to date.

DNA sequences can be inserted using particle bombardment (biolistics) or by culturing the plant tissue with *Agrobacterium* spp. with promoters, virulence genes and the targeted sequence inserted on plasmids. Gene expression can be increased or decreased, either constitutively or as an inducible response. Traits of interest for gene modification include herbicide tolerance, photosynthetic efficiency, wood quality — particularly lignin quality and quantity — sterility, early flowering, increased growth rate, disease and pest resistance, virus and pathogen virulence of insect pests, heavy metal metabolism, and stress tolerance (Ellis et al. 2001; Campbell et al. 2003; Government of Canada 2003; Tang and Newton 2003; Wang et al. 2003). Some tree traits have no apparent homologs in herbaceous plant models like *Arabidopsis*, which are used to identify and map putative candidate genes (Rottmann et al. 2000).

Following is a brief synopsis of the traits and pathways currently eliciting the most interest. The broad spectrum herbicide glyphosate is sometimes applied on productive sites during early plantation establishment. Susceptibility of planted seedlings to glyphosate either requires mechanical or spot-applied weed control where necessary, both costly alternatives to inherent or inducible resistance (Fillatti et al. 1987; Johnson and Kirby 2001). Altered lignin content, where xylem would contain increased cellulose or hemicellulose; or composition, where the ratio of lignin subunit types would be altered, can reduce energy costs and toxic by-products of pulping (Baucher et al. 1996; Hu et al. 1999; Pilate et al. 2002; Huntley et al. 2003; Li et al. 2003). Modification of fibre length and other wood properties is also the subject of research.
Rugh et al. (1998) have produced yellow poplar trees with modified mercury metabolism, leading to further interest in bioremediation applications. Alteration of flowering, either by inducing early reproduction or by preventing sexual reproduction altogether, is being investigated by many researchers. Early flowering has been achieved in poplar (Rottman et al. 2000), which would allow breeders to decrease generation times. Eliminating flowering has proven more difficult, since there are so many mechanisms associated with maturity and reproductive development which must be stably altered either indefinitely or until after harvest (e.g. Strauss et al. 1995; DiFazio et al. 1999). This would also enhance wood production (El-Kassaby and Barclay 1992) and reduce allergenicity (Gartland et al. 2002). Other researchers are testing various reporter genes and regulatory sequences to assay the stability, magnitude and potential interaction among transformed genes, organisms and ecosystems (James et al. 1998; Levée et al. 1999; Hawkins et al. 2002; Hay et al. 2002; Meilan et al. 2002).

Genetic transformation research currently centers on gene discovery, knockout and mapping to provide detailed knowledge of genomics and genetic control of physiology (Walter et al. 1998; Hershbach and Kopriva 2002; Giri et al. 2004). There are also potential conservation applications (Adams et al. 2002). Traditional breeding for chestnut blight resistance has been ineffective, so researchers are transferring genes from blight-resistant Asian congeners to susceptible American chestnut rootstock (Maynard et al. 1999; Mann and Plummer 2002a). Genetic engineering is also being explored as a means of conferring and enhancing resistance to Dutch elm disease (Gartland et al. 2001). Another avenue of investigation is altering genes influencing dormancy, stress tolerance and germination for rare species, hybrids, tropical species and horticultural varieties which are difficult or impossible to propagate from seed. Micropropagation (see Propagation section) is an integral component of genetic transformation, allowing transformed cells to be multiplied and grown into plants for testing (Sutton 2002; Giri et al. 2004).

Although thousands of field trials and many operational releases have been approved for plants with novel traits (PNTs) in Canada (including bacteria, fungi and viruses), only four tree species have been approved for confined field tests: black and white spruce, poplar, and cherry, all under the auspices of the Canadian Forest Service (Figure 1; McLean and Charest 2000). In the U.S.A., forest trees form a similarly small proportion of total tests, which are conducted primarily by academic consortia and companies (Owusu 1999; Ellis et al. 2001). Many fruit trees have been approved for testing (included in Fig. 1 in the total, but not as trees). Forest tree species approved for U.S. field trials include poplars, sweetgum, eucalyptus, southern pines and American chestnut. The E.U. has approved a similar complement of commercially important tree trials for fibre and fruit production (Gartland et al. 2002). Environmental and genetic risk factors, long-term stability of transformed sequences, and liability issues associated with the genetic material and land and resource ownership are all cited as reasons for regulatory caution (Levée et al. 1999; McLean and Charest 2000; Heron and Kough 2001; Hawkins et al. 2002). In Canada, approved PNT trials have declined over the past several years, while number of trees approved has remained steady; in the U.S.A., total permits have levelled off, while approvals for trees have increased (Fig. 1).
Conclusions

Forest biotechnology is maturing, building on momentum and innovations in agriculture. Deliverables can be organized into five major categories: molecular markers, propagation, genomics, marker-aided breeding and selection, and genetic modification. The first two are currently implemented by some forest practitioners, and the latter three remain fields of active research, but are not yet operational. Continuing progress in high-throughput technology and bioinformatics are making forest biotechnology deliverables more applicable to diverse issues in biology and forestry. Due to the cost, time and large sample sizes required for testing and development, forest biotechnology will likely find an operational niche with intensively managed plantations featuring clonal or family forestry, capable of delivering high investment returns on short cycles.

References


Economic Benefits and Costs of Forest Biotechnology

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Washington, DC

Over the past decade, the US has seen steady and continuing divestitures of industrial timberland, not just in the Northeast, but in some of the most highly productive areas of the Pacific Northwest and the US South (Block and Sample 2001). This has been driven in large part by the ongoing global consolidation of the forest products industry and the availability of large tracts of land suitable for forest plantations, largely in Southern Hemisphere countries with lower costs for land, labor and capital.

There have been several calls recently for developed temperate-forest nations with high per-capita consumption of wood and wood fiber to expand the use of intensively-managed plantations as a way to meet more of domestic demand from domestic sources (Sedjo and Botkin 1997; Victor and Ausubel 2000). Some of this interest in intensively-managed plantations has actually come from environmental organizations that have often challenged forestry operations. In this instance, however, they see greater utilization of forest plantations to meet wood demand as a means of reducing development pressures on the remaining natural forests, and thus opening opportunities to better protect native biological diversity (Howard and Stead 2001).

This is largely a moral argument—that high wood-consuming nations have a responsibility to meet as much of their own demand as possible, before shifting development pressures to other countries, particularly tropical forest countries where...

More specialized approaches to forest management can result in significant increases in both biodiversity conservation and sustainable wood production.

Management Intensity Spectrum

A. Commercial forest plantations intensively managed for the production of wood and wood fiber-based commodities.

B. Forests managed at a moderate or low intensity for a wide variety of goods, services, and natural values.

C. Native forest reserves managed for conservation and restoration of biological diversity.
biodiversity values tend to be significantly higher than in most temperate forests (Sample 2003). But moral imperatives, unless codified in law or public policy, tend to crumble in the face of economic factors that drive capital investment in a different direction.

Global demand for industrial roundwood is expected to double by 2050, from the current 1.6 billion cubic feet (BCF) per year, to approximately 3 BCF per year (FAO 2000). Supply is expected to keep pace, however, to the point where most analysts project flat or only slightly rising real prices for wood and wood fiber over the next couple of decades (Haynes 2003; Zhu et al. 1998). This abundance of wood supply is due in large part to major investments in forest plantations during the 1980s and 1990s, mostly in South America and elsewhere in the Southern Hemisphere, which are now producing large volumes of industrial roundwood and wood fiber.

If accurate, these projections have important implications for returns on investments aimed at further increasing wood supply.

- Social and political issues associated with genetically-modified trees notwithstanding, is there a persuasive economic case to be made for financial investments in the research and development necessary to bring these technologies up to a commercial operational scale?
- In industrial countries, are quality and consistency considerations sufficient to justify the investments?
- Enhancements such as reduced lignin content promise to reduce energy and chemical requirements for wood pulp processing, with positive implications for energy conservation and protecting environmental quality. Is this enough?
- Even with stagnant real prices for wood and wood fiber over the next decade or two, continued population growth, the rapid industrialization of China, India and other developing countries, and a finite supply of land suitable for forest plantations strongly suggest that these technologies will be important in the longer term.

for forest plantations strongly suggest that these technologies will be important in the longer term. Is this prospect sufficient to attract the necessary level of financial investment in the near term?

References


The Products and Value Proposition of Forestry Biotechnology

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The value proposition of forest biotechnology is best addressed by first establishing common definitions. A broad universe of advanced biological technologies applies to forestry, including cell biology, molecular biology, gene mapping, marker-assisted breeding, conventional propagation methods, tissue culture, and asexual propagation methods, as well as transgenic traits for input and output characteristics. However, these technologies only have direct relevance to forestry through two product areas: germplasm and transgenic traits.

**Germplasm** means elite genotypes which can be stored, bred and then rapidly and uniformly propagated in scale. This is a significantly different definition than has historically been used in forestry;
The value proposition for forestry biotechnology exists principally within these two product areas: germplasm and transgenics.

The advent of transgenics in forestry will revolutionize the industry’s crop protection practices, reduce climatological challenges (e.g., drought and salinity tolerance) and de-commoditize the end-products (wood quality, uniformity, stand constitution).

The vast majority of R&D costs of these new products are borne by the integrated forest products companies, large ag-biotechnology companies, forestry co-operatives, academic institutions and entrepreneurial biotech firms. Once these high-risk costs have been invested — by shareholders, taxpayers and venture capitalists — the cost of the products themselves (germplasm and traits) will be de minimus in comparison.

The pricing mechanism for these products will be an allocation of the value created between the innovator of the product, the production/distribution chain and eventually the end-user. This mechanism emerged as the successful value capture model for biotech row crops, based on the proposition that each product must make the producer more profitable by reducing inefficiencies in production (e.g., cost of crop protection) and/or by increasing value of the crop (e.g., fiber and oil quality). In practice, 50-70% of value over time is going to the end-user/grower.

A crucial step in full commercialization of these technologies will be vertical communication about value capture and allocation through the industry. Biotechnology products bring with them new levels of information which will drive new forms of communication and new levels of profitability.

The Potential for Commercialization of Biotechnology in Poplar

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Commercial Importance of Poplar Plantations

Poplars and their hybrids were among the first domesticated trees worldwide. Plantations were established in North America as early as 1893, and large-scale controlled hybridization dates to 1923-1927. Today poplar is of moderate commercial importance in North America; there are 86,000 plantation acres in the United States and 35,000 acres in Canada. Most of this acreage has been developed over the past 30 years by the pulp and paper industry, although a change in management towards higher-value products including saw and veneer logs, engineered wood products, energy, and environmental applications is now underway.

On a global scale, however, poplar commands greater commercial importance with over 9,000,000 acres under management for wood production while an additional 7,000,000 acres have been planted for environmental purposes. Countries outside of North America supporting large poplar programs are China, India, France, Italy, Turkey, and Argentina. Beginning in 1999, Chile embarked on a research program to diversify their radiata pine industry with a poplar program that ultimately may reach a scale of 200,000 or more plantation acres.

On a global scale, however, poplar commands greater commercial importance with over 9,000,000 acres under management for wood production while an additional 7,000,000 acres have been planted for environmental purposes.
Worldwide, poplar cultivation relies nearly exclusively on select inter-specific hybrid clonal varieties. Seven of the 29 species in the genus — *Populus alba*, *P. deltoides*, *P. nigra*, *P. suaveolens*, *P. tremula*, *P. tremuloides*, and *P. trichocarpa* — are used in breeding the major hybrid taxa: *P. x canescens*, *P. x canadensis*, *P. x generosa*, *P. nigra* *x P. suaveolens*, and *P. tremula* *x P. tremuloides*. Select varieties of southern sources of *P. deltoides* are often used in place of hybrids at lower latitudes. The mean annual increment of poplar stands varies mostly between 225 — 500 cubic feet per acre with rotations spanning 8 to 25 years dependent upon markets and site.

**Conventional Plant Improvement**

Conventional breeding will continue as the major commercial avenue for improving complex physiological traits such as yield and adaptability. Growth rate, stem form, adventitious rooting, pest resistance, climatic adaptability, and wood specific gravity are the main characteristics in which improvements are sought. First-generation hybridization and backcross breeding are the most common improvement strategies. Many programs function to produce new varieties as substitutions for the lowest-ranking ones in production deployment pools and as replacements for those culled as losses of disease resistance occur over time. Long-term improvement efforts involving reciprocal recurrent breeding programs for the multiplicity of parental species participating in first-generation hybridization programs are often too costly to pursue in a meaningful way.

**Biotechnology Commercialization and the Poplar Plantation Industry**

Poplar has long been the model species for forest biotechnology. Significant scientific achievements have been accomplished in organogenesis, *in vitro* axillary shoot proliferation, embryo micropropagation, genetic transformation, and genomics. A marketable opportunity for most of these technologies will be contingent upon the degree to which the poplar plantation industry expands globally through the promotion of its own key operational and marketing strengths. Moreover, poplar’s status as the lone hardwood of the temperate zone capable of growth rates that can be developed to compete with plantations of the tropics and sub-tropics also gives impetus to biotechnology applications.

The following are the mainsprings that will drive expansion of the poplar industry and, thereby, commercial opportunities for biotechnology.

1. **Green certification** of plantation-derived wood products that leads to larger market shares and preferential product pricing.

2. Development of globally recognized, proprietary poplar lumber grades that serve to develop and define world markets.

3. Exploitation of poplar’s unique crossover demand in both hardwood and non-structural softwood markets.

4. Refinement of a multiple-product approach to poplar marketing that merchandises each plantation’s yield component (e.g. sawn lumber, veneers, poles, dowels, chips, residual biomass) to the respective market of greatest economic return, while concomitantly seeking economic or tradable credits for improvements in soil, air, and water quality.

5. Increased production and processing efficiencies, the former derived from a regular and consistent wood supply from plantations managed on lands of marginal agricultural quality within proximity of mills, the latter derived from poplar’s unique wood structure and brightness.

6. Access to dynamic pools of high-yield, well-adapted varieties of diverse taxa and pedigrees to maximize productivity while minimizing the risk of plantation failures. It is not uncommon to find broadly adapted taxa, pedigrees, and in some cases, genotypes with which the commercialization of biotechnologies can be more profitably accomplished.

7. Development and promotion of poplar’s highest regional market values to secure investment capital for plantation development.

**Biotechnology and Conventional Poplar Improvement**

Commercialization of biotechnology will be optimized through a close integration with conventional breeding programs. Genetic transformation will, by necessity, require access to proven individual elite varieties that have undergone rigorous testing so as to justify the investment of time and money. The challenge will be to refine the present testing protocols in a way that efficiently accommodates the additional steps of transformation, screening variants, and mass multiplication of the top selections. Conventional breeding programs operate on an annual cycle of breeding, selection, and deployment to ensure a continuity of elite selections to keep pace with evolving pathotypes. Here the challenge will be to...
The discovery of genes for enhanced carbon storage and enzymes important to ethanol conversion using the pedigreed populations of conventional improvement programs will help to commercialize poplar for carbon and energy markets.

Ensure timely transformation and commercialization before selections become obsolete.

Integration with genomics will be similarly critical to the degree that positional cloning of poplar genes for transformation may be less controversial in the long run. The discovery of genes for enhanced carbon storage and enzymes important to ethanol conversion using the pedigreed populations of conventional improvement programs will help to commercialize poplar for carbon and energy markets. Likewise, transformation for tailored polymeric chemistry will lead to superior composite and engineered wood products.

Endnotes


What are the societal and regulatory issues? How can they be addressed?
Regulation and International Trade: Issues for Transgenic Trees

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Abstract
This paper examines issues and problems related to international trade of transgenic wood and transgenic tree germplasm. While there is little reason to believe that transgenic wood flows would be negatively impacted, the transfer of technology in the form of transgenic germplasm is likely to find resistance entering some markets. This could result in increased regional degree of specialization in wood production that could lead to larger volumes of exports from increasingly dominant global wood producers.

Introduction and Background
The advent of planted forests has provided a financial incentive to undertake tree improvement, since the benefits from investments in tree improvements can be captured in the higher productivity at harvests associated with the improvements. Tree improvement in industrial forestry has been underway in a significant way for about one-half century, or roughly since the period where planted forests for industrial wood production began to become common. Increased productivity has resulted from the planting of exotic species, many of which have far greater yields in their new locations. Additionally, tree improvements to both indigenous and exotic trees have been brought about through activities such as superior tree selection, traditional breeding techniques and clonal propagation of superior trees. These innovations have had a positive influence on industrial wood production, particularly in some regions, thereby impacting on regional and international patterns of forest resource production and forest products trade.

In the U.S., plantations have been a factor in the shifting of the center of forestry from the west to the south. Globally, perhaps most notable is the growing role that South America is playing in the production of plantation grown industrial wood and the export of wood and wood products. However, other regions have also participated, including New Zealand, Australia and South Africa.

Thus far neither biotechnological regulations nor international trading rules have seriously impacted these shifts. Although international trade markets do differentiate among species, they do not differentiate between indigenous and exotic wood. Nor has international trading of the tree improvement innovations of the type undertaken been seriously restricted by trade regulations on either the wood product or the traditionally improved seed. However, some aspects of transgenic (bioengineered) trees are likely to be treated quite differentially by international trading and existing regulatory regimes.

In most countries transgenics, unlike most traditionally modified plants, are automatically regulated and required to pass successfully through a deregulation process for commercialization to occur. However, the deregulation criteria and processes often differ substantially among countries. For example, the stated acceptable level of risk associated with the deregulation of
a transgenic plant is different in the U.S. than it is, e.g., in the European Union (EU) (Sedjo 2004a, Pichinco 2003). Nevertheless, currently many transgenic agricultural crops have successfully completed deregulation and are integrated into domestic and international agricultural markets. However, disputes continue as to whether and under what conditions countries can refuse to import transgenic crops and prohibit the use of transgenic seed, e.g., within the context of the World Trade Organization (WTO).

In this paper I discuss issues and problems related to international trade of transgenic wood and of transgenic tree seed.

Tree Biotechnology

Biotechnologies can be separated into two categories: traditional or sexual breeding, and genetic engineering, which uses non sexual techniques to transfer genes. Traditional approaches include superior seed selection, which has been the basis for tree improvement using traditional breeding techniques like selection of superior (plus candidate) trees for volume and stem straightness, and grafting these into breeding orchards and producing seed orchards. When breeding orchards begin to flower, pollination of selections is artificially controlled, seeds are collected, progeny tests are established, and the best offspring are chosen for the next cycle of breeding. By identifying and selecting for desired traits, breeding can select for a set of traits that can improve wood and fiber characteristics, improve the form of the tree, provide other desired characteristics, and improve growth. These traits are introduced into the genetic base that is used for a planted forest.

A variant of the traditional breeding techniques is that of hybridization, which has provided robust offspring by bringing together populations that do not normally mix in nature. This approach is widely used in forestry. As in agricultural products, tree hybrids are often a means to improve growth and other desired characteristics. Hybridization crosses trees that are unlikely to breed in nature, often where parents do not occur together in sympatric populations. These crosses often exhibit growth and other characteristics that neither of the parent species alone can match.

The development of cloning techniques in forestry is important for a number of reasons. First, if superior trees are available, an approach must be developed to allow for the propagation of large numbers of plantlets with the desired characteristics if these traits are to be transferred into a planted forest. With tree planting often involving over 500 seedlings per acre, large-scale planting of improved stock requires some method of generating literally millions of plants, at a relatively low cost.

The ability to use inexpensive cloning techniques varies with species and genus. Cloning also includes the use of genetic markers to try to find a relationship between the markers and certain characteristics of the tree. A major approach to genetic manipulation of trees utilizes molecular biology.

Finally, there are transgenic or genetically engineered trees with generic transformations that involve the introduction of selected foreign genes into the plant genome. In this approach specific genes are identified and modified to affect biochemical pathways and the resulting phenotypes. Thus far, transgenic trees have not been used commercially for wood production (McLean and Charest 2000). However, the promise is substantial, as has been demonstrated in agriculture. Potential applications include herbicide resistant genes, pest resistant genes (Bt) and genetic alteration that would provide certain desired wood characteristics. Gene alteration can result in unique gene combinations unachievable by traditional tree breeding that are

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1 It is estimated that 4 to 5 million trees are planted in the U.S. every day.
expressed as desired traits. Thus, for example, in concept, frost resistant genes could be transferred from plants or other organisms found in cold northerly regions to tropical plants, thereby increasing their ability to survive in cooler climates.

**US Plant Regulation**

The Animal and Plant Health Inspection Service (APHIS) of the Department of Agriculture has been regulating biotechnology since 1987, overseeing more than 10,000 genetically engineered crop field tests and deregulating 61 genetically engineered plant varieties (Veneman 2004). The basic legislation is Plant Protection Act (Title 7 U.S.C. Sections 7701 et seq.), which currently provides the basis for the Animal and Plant Health Inspection Service (APHIS) of the Department of Agriculture’s authority over genetically engineered organisms. (Bryson et al., 2001 p. 33). The Plant Protection Act (PPA) provides statutory authority to APHIS to regulate a genetically altered plant, crop, or tree on its potential to become a plant pest or pose unacceptable risks to the environment.

APHIS administers regulations for most genetically engineered plant organisms, which are initially classified as “regulated articles.” Developers of regulated articles must obtain prior authorization from APHIS for the importation, interstate transport, and field-testing of these plants. Field-testing is a precondition of deregulation, which in turn is necessary for the transgenic to be commercialized without restrictions. Based upon the results of field tests and other information, an APHIS scientific committee determines whether to deregulate specific transgenic plants. Once a determination of nonregulated status is made, the product and its offspring no longer require APHIS authorization for movement, release, or commercialization in the United States.²

**Outputs of Tree Biotechnology: Two Types of Goods**

There are two separate and distinct products that can be the outgrowth of a transgenic tree. The first one is the transgenic wood that has been produced. The second is the transgenic seed or germplasm, which embodies the desired gene. Both of these can be traded on world markets, however, the trading characteristics differ since one of the outputs, the germplasm, is generally regulated, while the other, the wood, is not regulated in most cases.

² In January 2004, USDA announced (USDA 2004) its “intention to update and strengthen its biotechnology regulation for the importation, interstate movement and environmental release of certain genetically engineered (GE) organisms.” Associated with that announcement, Secretary of Agriculture Ann Veneman (2004) made remarks regarding biotechnology regulations. She noted that a regulatory framework must advance with the science and technology and announced that APHIS was beginning a comprehensive update of their regulatory framework, with greater emphasis to be put on risk and additional flexibility for products that have already demonstrated their safety.
The advent of tree genetic engineering has been in the research phase for only a few years and has tended to follow the experience of transgenic crops. For example, much early work on tree genetic engineering focused on the transfer of an herbicide resistance gene, in a fashion akin to that in some agricultural crops, e.g., soybean (Sedjo 2004b). The more recent focus of biotechnology research, however, has been on modifying wood fiber characteristics. The conventional approach today is to use traditional breeding approaches to achieve increased growth and biomass yields, while genetic engineering focuses on obtaining desired wood characteristics. These would include an increase in the amount of useful fiber or the production of fiber that is more cheaply processed in the digester in the production of wood pulp, thus increasing output yields.

**A Look at Transgenic Agriculture**

Most transgenic innovations in agriculture have been developed by the private sector in a few developed countries. The use of these innovations is now flowing from industrial to developing countries. Also, there is a flow of the products (commodities) of this technology to both developed and developing countries. Trade restrictions on commodity flows (agricultural GMOs) require a health and/or safety justification. Restrictions in the absence of these conditions violate the Global Trade Organization’s (GTO) rules on protectionism. Nevertheless, there are often attempts to restrict the importation of GMO agricultural products and the disputes continue.

**International Trade of Wood and Transgenic Tree Germplasm**

The outputs of transgenic innovations involve both wood commodities and tree germplasm. A simple model of international trade predicts goods will flow from the country of comparative advantage (low opportunity cost) to other countries with higher costs (Sedjo 2004c). In the case of international trade in wood, the basic product is raw wood, but availability of raw wood often allows a range of products to be produced at low cost, such as building materials, pulp and paper, a variety of wood products and packaging materials of both paper and wood. The complex variety of products, as well as the benign nature of transgenic wood, makes it unlikely that any serious prohibitions to the international trade would be constructed as the result of transgenic wood.

However, the transmission of tree germplasm in the form of seed or seedlings is viewed as a very different event. For trees, the concerns expressed might be largely oriented toward the impact of the planted tree on the natural environment through gene escape (Williams 2004). Internationally, genetically engineered plants in some forms may be covered by various international agreements that constrain their movement and trade. The two major global agreements that come into play are the “Cartagena Protocol on Biosafety (Montreal 2000) to the Convention of Biological Diversity,” and the International Plant Protection Convention (IPPC). The Cartagena Protocol, recently ratified by almost 100 nations, requires the labeling (but does not prohibit) of live transgenic bioproducts, such as a crop or tree seed and other live germplasm. The IPPC was created to secure common and effective action to prevent the spread and introduction of pests of plants and plant products (PEW 2004). Additionally, the World Trade Organization (WTO), designed to promote international trade with consistent

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3 For example, wood used for pulp, paper and materials is dead, and not eatable by humans.

4 The United States is not a party to the agreement; however, most US firms are likely to comply with the labelling requirement since it will be required by many countries.
procedures that avoid protectionism, is becoming a factor with international trade of transgenic plants.

The concern about the escape of transgenes might vary by region. It is generally agreed that little gene transfer is likely to occur in the natural environment when very different species are involved (DiFazio et al 1999). Thus, for example, since pine is not indigenous to South America, the probability of gene transfer to indigenous tree species, of which there is no pine, is nonexistent. The same argument is applied to eucalyptus, an exotic in all regions of the world except Australia and adjacent northern islands. Thus, concerns related to the international trading of germplasm are likely to vary by the conditions particular to the region, particularly the species compositions.

One question that has been raised is the extent to which tree improvements and improved transgenic trees are likely to generate major shifts in the comparative advantages of the various regions. In fact, with the advent of planted forests over the past 50 years, the world has already seen a major restructuring among the leading regional timber producers. First, exotics have been widely planted in regions where they are particularly suited. Second, intensive management is increasingly being practiced, especially on highly suitable sites. Finally, tree improvement programs further improved the growth and yields, again particularly in regions well suited for planted forests.

As a result of these forces, wood harvested from planted forests has increased from a negligible fraction of total harvests to roughly 34% today (FAO 2001). These increases have occurred in both traditional timber producing regions, e.g., the US South, and in newly established planted regions e.g. South America and New Zealand. There is every reason to expect these shifts to continue, and indeed be facilitated by transgenic forestry.

Obviously, transgenic forestry also has the potential to accelerate some of these trends. However, it could also modify them. For example, to the extent that transgenic forestry can improve tree performance in temperate and boreal sites, it may be able to facilitate a resurrection in lightly inhabited northern regions. Relatively rapidly growing trees on low opportunity cost northern sites could improve the competitive position in these areas of otherwise low economic activity.6

The State of Transgenic Wood and Tree Germplasm Activities Today

With the exception of one orchard tree, the papaya, no transgenic trees are known to be officially deregulated. That said, informal sources have stated that transgenic trees have been deregulated and planted for commercial purposes in China,7 and there are a number of situations in which a transgenic tree is close to commercialization. Brazil appears very near the commercialization of a transgenic eucalyptus. The intent in Brazil is to introduce a transgenic tree in

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6 Some details of what is covered are still being worked out. For example, a live modified organism that is not intended for release in the environment may not be covered (Pew 2004).
7 In fact, generically improved trees (although not transgenics) are currently being planted in Minnesota and central Alberta in an attempt to provide additional timber resources for current ongoing resource development activities. In Alberta, planted forests are anticipated to compete away land formerly in crop agriculture.
7 China has a process for the deregulation of transgenic plants (Pachico 2003).
the next year or two that would use the very rapidly growing trees now in use as a platform for the insertion of genes that will dramatically increase (+40%) the fiber content of the tree. It is interesting that when this project was begun, Brazil still had a prohibition against the use of plant transgenics of any type; that situation is changing. Also, New Zealand has developed a transgenic radiata pine, which is awaiting deregulation that is on hold in that country.

Finally, large investments in the development of a transgenic loblolly pine are underway in North America. The innovations would largely involve fiber modifications with the intention of improving the pulping characteristics of pine fiber, thereby lowering pulping costs. The technical challenges involve: first, the development of an appropriate mechanism to transfer gene(s) that generate the types of desired fiber modifications; and second, the development of a technique that would allow the massive replication required for plantation establishment in a low cost and timely manner.

Since the deregulation systems will vary by country, a transgenic tree that is deregulated in one country may not be recognized in other countries.

Barriers to Trade in Transgenic Trees and Wood

Potential barriers to transgenic forestry and wood come at two levels. First, would be barriers to transgenic wood flows. These would seem to be unlikely due to the benign nature of transgenic wood as discussed above.

Second, would be barriers to the flow of tree germplasm. These barriers could be formidable, but depend on the various individual countries. Individual countries have deregulation standards and procedures, however, countries may choose to allow the importation of germplasm that has passed regulatory hurdles in other countries. This is the case with many transgenic crops. However, this may well not become the generally accepted rule. In many cases, individual countries may want to deregulate a transgenic tree before it is allowed to be planted commercially. Since the deregulation systems will vary by country, a transgenic tree that is deregulated in one country may not be recognized in other countries. Such a system would be fraught with uncertainty and quite costly. In many cases it may simply not be worth the cost to deregulate a tree in a country with a modest growing potential.

Overcoming Barriers to Transgenic Wood Trade

Given the wide degree of interest in transgenic trees, it appears likely that some transgenic wood trees will eventually become commercialized in some countries of the world. Thus far one transgenic tree has been “officially” deregulated in the world, specifically the orchard tree the papaya, which was deregulated by the US (by APHIS) and is now commonly planted in Hawaiian orchards. It may, however, not be in the major producing countries but rather in countries of South America or Asia where major deregulation takes place for timber trees. It has been unofficially reported, for example, that some 300 ha of transgenic poplar have been established in a commercial forest in China. Such a system would be fraught with uncertainty and quite costly. In many cases it may simply not be worth the cost to deregulate a tree in a country with a modest growing potential.

Based on some of the considerations discussed above, it appears that the wood of transgenic trees is unlikely to be effectively excluded from international trade. The wood can take many forms, would be difficult to detect and, since it appears to be harmless, it is likely that the de-

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8 This appears to be the type of system often practiced in agriculture today.

9 At a November 2003 meeting of the FAO Panel of Experts on Forest Gene Resources, a Principal Research Scientist of the Research Institute of Forestry in China reported on the establishment of close to 300 Ha of commercial transgenic poplar in China. (Personal communication, Yousry El-Kassaby, January 20, 2004)
cision as to whether to commercialize will depend on the basic financial returns to the innovation, the degree of restriction, and the costs of deregulation in individual countries. It seems likely that some counties will deregulate and allow the production, sale and export of transgenic wood. Other countries may not allow production, but are likely to find it difficult to prohibit importation of transgenic wood and especially wood and paper products. Thus, it appears likely that the market will eventually find transgenic and non-transgenic wood competing in various wood markets.

**Forest Certification as a Barrier to Transgenic Wood**

In recent years there has been a strong movement toward forest certification to insure that wood is managed in a sustainable or “well managed” manner. There are a number of organizations that have created standards, sponsor forest audits and represent themselves as ‘certifiers” of the management of commercial forests. At least one of the major certifying groups, the Forest Stewardship Council (FSC), has standards that will not allow certification of a forest that contains transgenic trees. Of course, at this time such a requirement is moot since there are essentially no deregulated transgenics to plant. However, the FSC has gone so far as to withhold recognition from forest firms that have research activities related to the development of transgenic trees.

How effective using certification as an approach to preventing the commercialization of transgenic trees will be in preventing the development and utilization of transgens remains to be seen. While FSC is the only forest certifier active in most parts of the globe, there are a number of other major forest certifiers, often regionalized but usually in competition with at least one other certifier (e.g., see Cashore and Lawson 2003). Some of the major certifiers are more accepting of transgenics, requiring only that the tree planters follow the existing law and practice sound science, e.g. SFI. It is feasible that a strong public preference for certified wood and a preference for the certification of the FSC could inhibit the development of a transgenic wood market. However, there is little evidence currently that the preference for certified wood translates into higher prices as sometimes alleged (Sedjo and Swallow 2001). The lack of a price premium may reflect a relatively weak overall preference for certified wood, which may or may not transfer to transgenic wood.

**Implications of Barriers for Transgenic Trees**

It appears unlikely that any of these barriers, with the possible exception of certification, will provide a significant obstacle to the free flow of transgenic wood. However, several of these barriers are likely to provide a substantial obstacle to the international flow of transgenic tree germplasm. This would result in a world where the good (wood) would be traded but important technology (transgenic trees), would not. To the extent that transgenic trees provide low cost and perhaps superior wood, some regions will have a strong financial incentive to adopt

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10 The major forest certifiers are: FSC — Forest Stewardship Council; (SFI) - Sustainable Forest Initiative; CSA — Canadian Standards Association; ATFS — American Tree Farm System; PEFC — Pan European Forest Certification; MTCC — Malaysian Timber Certification Council; LEI — Lembaga Ekolabe Indonesia; ISO — International Standards Association Source: Certification Watch (2002).

11 Note that certified wood is physically identical to noncertified wood, the only difference being in the environmental sensitivity of the forest management. Transgenic wood, would in fact, be physically slightly different involving proteins that could be detected in chemical tests.
the technology. This could provide an additional comparative advantage to the countries and firms that adopt transgenic trees.

Furthermore, to the extent that countries that already have a comparative advantage in wood production benefit disproportionately from transgenic trees and therefore would adopt the appropriate technology (transgenic trees), and countries without a comparative advantage fail to adopt transgenics, the comparative advantage gap would widen. Thus, one could envision a world in which wood production specialization becomes even more intense with a few high wood productivity countries, which have adopted the latest transgenic technology, further increasing their share of worldwide timber production.

Summary and Conclusions

This paper suggests that for transgenic trees to have an opportunity to have a major impact on global production requires that they be developed, deregulated, and commercialized. It discusses the regulatory barriers to commercialization, which may vary by country, and examines the potential implications of these barriers on international trade in transgenic wood and in transgenic tree germplasm. Development is being undertaken in many countries of the world with the focus apparently on improving wood fiber. Since deregulation is undertaken country by country, without the acceptance of some countries of the deregulation undertaken in others, the international transfer of transgenic tree germplasm could be stiffened. There is little reason to believe that transgenic wood flows would be negatively impacted unless there was widespread opposition that translated into widely accepted transgenic prohibiting certification standards. However, transgenic trees offer the possibility of increasing country specialization by enhancing the comparative advantage of existing exporters, while importers fail to use the technology due to lack of local deregulation. This could result in increasing the regional degree of specialization in wood production and result in larger volumes of exports from increasingly dominant global wood producers.

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It is assumed that the benefits of transgenic technology will accrue disproportionately to the inherently high productivity sites.


Changing Biotechnology Regulations — Impact on Forestry

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APHIS regulates genetically engineered organisms under authority granted by the Plant Protection Act 2000 and coordinates the regulation of field testing of genetically engineered plants with EPA and FDA under the Coordinated Framework for Regulation of Biotechnology 1986. The first regulated field test occurred in 1987 and after the first six years of evaluating permits, experience demonstrated that criteria and performance standards could be defined for certain field test that do not present novel plant pest risks. This gave rise to the notification option that became effective in 1993. The notification option originally covered six major crops and was modified in 1997 to cover nearly all plants. The notification option represents a simpler, streamlined application and review process for importation, interstate movement and field testing but meets the same safety standards as field trial under permit. Transgenic plants which raise certain safety issues, for example pharmaceutical-producing plants, engineered microorganisms, and engineered insects are not eligible for this option. As technology changes and as new applications in biotechnology emerge, regulations must also change and adapt. APHIS recently announced a plan to do a programmatic Environmental Impact Statement in anticipation of changes in the regulations for field testing and deregulation of transgenic plants.

There are several reasons for changing the regulations at this point:

- The plant protection act of 2000 consolidated and extends USDA authority to regulate Plant Health.
- Allows APHIS to regulate transgenic plants under the “noxious weed” authority.
- Regulations need to evolve to cover plants transformed by biolistics and other means and genes from a variety of sources.
- APHIS needs more flexibility to cover different levels of risk on a case by case basis.
- Plant-made pharmaceuticals and industrial compounds need special attention.
- Flexibility needs to be incorporated in the new regulations to allow for situations we can not imagine at this time.

The goals of the regulations are to have science-based triggers that are rigorous, consistent, and easily understood; to be effective, flexible, and dynamic; to impose a degree of oversight proportionate to the potential risks; and to meet both domestic and international needs.

The objective of the proposed revisions is to allow for safe development and use of new transgenic varieties, simplify regulations, minimize regulatory burden where appropriate, increase public involvement and transparency, allow flexibility in evaluating and addressing risks, and closer coordination with the FDA and EPA.
The current status and expectations of this process are:

- Public comment period on Notice of Intent closed 4/12/04. APHIS received over 3,700 comments.
- APHIS held two weeks of stakeholders’ meetings with industry and NGO representatives.
- APHIS held a two-day meeting with State Departments of Agriculture.
- We hope to have the DRAFT EIS published by the summer 2005.
- The new rules will be drafted and sent out for public comment during CY 2005.
- For more information, [www.aphis.usda.gov/brs/](http://www.aphis.usda.gov/brs/)

See “Revising Regulations”
Publics and Opinions on Biotechnology: Missing the Forest for the Trees

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Abstract
What do publics think about biotechnology and why does it matter? This paper explores some of the stereotypes around publics and biotechnology and how these images lead to missed communication opportunities. Some of the trends in public opinions and perceptions and the factors that help to explain these views will also be discussed.

Introduction
No other word has been the subject of more public opinion polling as biotechnology. A recent poll taken in 2004 in the US and Canada asking in general, if people supported the use of products and processes that involve biotechnology, there appears to be cautious support for biotechnology (Fig. 1). There is a hierarchy of benefits and risks that is reflected in what is being modified and the purpose of the modification. As imagined, modifications to micro-organisms and plants are of less concern than modification to animals and humans. We see more support for human health and medical uses, followed by environmental uses, food and crops, and the least support for industrial uses of biotechnology (Fig. 2). Confidence in the regulatory system is a factor in determining how positively biotechnology is viewed with the US and Canada showing about 50% of publics being somewhat confident with the regulatory process in place.

Figure 1.

Acceptability of applications — 2004

Figure 2.
a. Use of GM bacteria or plants to break down pollutants, toxic waste
b. Helping to cure Type 1 diabetes by inserting GM cells into pancreas
c. Use of GM enzymes to turn corn into source of fuel
d. Wheat genetically modified to resist disease
e. Corn genetically modified to resist pesticides
f. Genetic modification of stem cells from bone marrow to treat blindness

A study to determine what factors help to explain interest in encouraging GM food and what is the relationship between “genetic knowledge” and encouragement or discouragement of GM food was undertaken in Canada. The results show that the factors that are most predictive of position on GM foods were the ones related to the specific attributes: utility, risk, and moral acceptability. Genetic understanding or knowledge of biotechnology was not a predictive factor. The notion that knowledge base can be directly correlated with support for biotechnology was not observed (Fig. 3).

Environmental applications of biotechnology are the second most positively received applications area after health and medical applications. It should be noted that the primary concerns with environmental products is the long-term risk to the environment. These two opinions should be considered in concert with each other (Fig. 4).

Consensus conferences or citizen juries have been used globally to study the issues surrounding biotechnology. Most of these have focused on GM foods. This approach follows a three-tiered process: 1) education, orientation, and charge to the jury; 2) deliberations and discussions with a broad range of experts; 3) jury deliberations and recommendations. From these consultations, some common concerns emerged:

- Is this food safe?
- What are the long-term impacts to my health?
- How is this food produced?
- What are the economic consequences of adopting this technology?
- What are the environmental impacts?
- Who benefits, who bears the risks?
- Who controls the technology?
- How are publics informed, consulted?

Some of the myths about publics on biotechnology are: 1) educate them and they will follow;
2) tell them about the risk probabilities and they will see how insignificant the risks are; and 3) tell them their fears are irrational.

Biotechnology is changing the traditional risk pillar from risk assessment → risk management → risk communication to a model that starts with risk communication and moves to risk assessment → risk management → and returns to risk communication. This is now the typical sequence for controversial applications of technology.

The current context for forest biotechnology is working against the backdrop of the controversies around GM food and crops. It has a different context for risk assessment and risk management. There are active and interested stakeholder groups and there is a greater policy interest in the role of publics. When thinking about sustainability not only should economic and environmental issues be considered, but also social issues. Some lessons from publics are: 1) a broader framework for assessing technologies; 2) the importance of values beyond risk and science; 3) a desire to trust technology overseers; 4) interest in accountability and legitimacy; and 5) opportunities to be heard.

Sources of public opinion data:

- Semi-annual national surveys — Canadian Biotechnology Secretariat (www.biotech.gc.ca)
- Eurobarometer (www.europa.eu.int/comm/public_opinion/index_en.htm)
- International collaborative group on public understanding of biotechnology — 15 European, US and Canada
- Pew Initiative on Food and Biotechnology (www.pewagbiotech.org)
- Qualitative studies — public consultations on biotechnology

Reference:


### Figure 4. Concerns with GM environmental products: Canada — U.S. ‘04

<table>
<thead>
<tr>
<th>Concern</th>
<th>% Canada</th>
<th>% US</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term risks to environment</td>
<td>46</td>
<td>47</td>
</tr>
<tr>
<td>Long-term risks to human health</td>
<td>34</td>
<td>33</td>
</tr>
<tr>
<td>Process involved raises ethical concerns</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Something unnatural about these products</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

### Perceptions of effects of GM Plants (Pew, 2002, US)

<table>
<thead>
<tr>
<th>Possible Effects (Plant statements)</th>
<th>% Saying “Important”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genetically modifying plants so they can clean up toxic pollutants in the soil</td>
<td>88%</td>
</tr>
<tr>
<td>Reducing soil erosion</td>
<td>88</td>
</tr>
<tr>
<td>Reducing the amount of water used to grow crops</td>
<td>85</td>
</tr>
<tr>
<td>Developing disease-resistant varieties of trees that are threatened or endangered</td>
<td>86</td>
</tr>
<tr>
<td>Reducing the need to log in native forests</td>
<td>82</td>
</tr>
</tbody>
</table>
Regulatory, Policy and Social Issues in Biotechnology

Pat Layton  
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During the last two years, the U.S. Secretary of Agriculture’s Advisory Committee on Biotechnology in the Twenty-first Century has reviewed a number of issues to consider in the area of biotechnology. These issues are primarily concerned with genetic transformation of plants and animals and not with other aspects of biotechnology or genomics. As genetic engineering of trees moves forward many of these issues may be important to consider. The issues include: regulatory changes; adventitious presence; asynchronous approvals internationally; local efforts to impose regulatory burdens; cost of product development; speed of the regulatory process given the potential for rapid development of new products; increased transparency in the regulatory process to aid stakeholders perceptions of biotech products; protection of intellectual property rights internationally; and will the products in development meet the needs of the future — can we predict what will be needed in 10 to 15 years. The Advisory Committee is still deliberating its report, but it is due to the Secretary in 2005 and hopefully its content will be useful in forest biotechnology.

Landscapes, Genomics and Transgenic Conifer Forests

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Balanced science-based dialogue is needed to determine whether genetically modified (GM) forests are the only way to benefit from the growing wealth of genomics information worldwide. By default, forests are following agronomy yet there are important life history, economic, temporal and financial differences. For example, conifers, as perennial plants, produce more seed and pollen with age. Their wind-dispersed seeds and pollen move across the landscape on the order of kilometers. At present, the risk of gene pollution is so high that GM field trials must be cut down before reproduction starts. And reproduction starts at least a decade before harvest. GM conifer forests are simply not GM food crops. Forest ownership in the United States is divided between private and public sectors. Each sector has a different technology portfolio and requires a different yet compatible genomics portfolio. This brings up another related issue: genetic swamping of unmanaged forests by domesticated plantations. Forestry’s genomics portfolio should be justified and developed with these differences in mind.
What are the current knowledge gaps and technology needs?
The Genome Canada Model

Martin Godbout
President and CEO
Genome Canada
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Genome Canada is the primary funding and information resource relating to genomics and proteomics in Canada. Dedicated to developing and implementing a national strategy in genomics and proteomics research for the benefit of all Canadians, it has so far received $375 million CDN from the Government of Canada. The Government of Canada committed an additional $60 million to Genome Canada in the 2004 Federal Budget. Genome Canada has established five Genome Centres across the country (Atlantic, Québec, Ontario, Prairies, and British Columbia) and has as a main objective to ensure that Canada becomes a world leader in genomics and proteomics research. Together with its five Genome Centres and with other partners, Genome Canada invests and manages large-scale research projects in key selected areas such as agriculture, environment, fisheries, forestry, health, and new technology development. Genome Canada also supports research projects aimed at studying and analyzing the ethical, environmental, economic, legal, and social issues related to genomics research (GE³LS).

The $365 million invested by Genome Canada in combination with funding from other partners, is expected to result in more than $800 million in 78 innovative research projects and sophisticated science and technology platforms.

Summary of Funding Sources for Genome Canada Approved Projects
(November 2004)

- Institutional $31M
- Federal $68M
- Foreign $77M
- Industry/Private $103M
- Provincial $190M
- Genome Canada $386M

Note: Categorisation of $62M in co-funding from the most recent competition in applied health is estimated.
Genome Canada has held three national Competitions to date. The Applied Genomics and Proteomics Research in Human Health Competition projects, as with Competition II and Competition I projects, were selected based on their international competitiveness and scientific excellence in the framework of Canada’s social and economic fabric. In fact, the research projects were selected following an in-depth evaluation process involving more than 150 international experts in each competition.

In January 2004, Genome Canada announced the results of the Genoma España — Genome Canada. The Competition was the result of the Framework Agreement to Promote Scientific and Industrial Cooperation between Canada and Spain, which was signed in May 2002. Genome Canada also has international agreements with other leading European countries including, Sweden, the Netherlands and Denmark.

Genome Canada, through its International Consortium Initiative, is also part of the $95 million Canadian-led Structural Genomics Consortium (SGC). The SGC is an international partnership with the United Kingdom via the Wellcome Trust, GlaxoSmithKline and four Canadian organizations. It is the first consortium of its kind, focusing its efforts on determining the three-dimensional structure of more than 350 human proteins. Genome Canada is also involved in two other major international initiatives: the Haplotype Map project and the Bovine Sequencing project. The Haplotype Map project is a $150 million program to identify repetitive gene associations within the human genome. Announced in October 2002, it requires major financial and scientific contributions from the United States, the United Kingdom via the Wellcome Trust, Canada, Japan, China and others. The Bovine Genome Sequence project was announced in December 2003 and is a $53 million US international effort to sequence the bovine genome. This collaboration includes researchers from the US, Australia and New Zealand.

The Genome Canada Board of Directors is composed of 15 members from industry and the scientific community in Canada. The Chair is Dr. Henry Friesen, formerly President of the Medical Research Council. The President & CEO is Dr. Martin Godbout.
The *Populus* Genome: Are There Discernable Differences Between the Genomes of Perennial Woody Plants and Herbaceous Annuals?

G. Tuskan¹, J. Bohlmann², S. DiFazio², C. Doulgas³, B. Ellis¹, M. Frazier⁴, D. Gilbert², I. Grigoriev³, L. Gunter¹, S. Jansson¹, J. Karlsson⁴, F. Larimer¹, N. Putnam², P. Rouze⁷, R. Dalhman⁴, S. Ralph⁸, D. Rokshar¹, S. Rounbauts⁷, J. Schein⁸, Y. van der Peer⁷, S. Wullschleger¹, T. Yin²

In May 2002, the DOE-JGI and -ORNL in collaboration with Genome Canada-Genome BC, the Umeå Plant Sciences Center, and the University of Ghent, initiated the *Populus* Genome sequencing, assembly, and basal annotation project on the recommendation of the international *Populus* community ([www.ornl.gov/ipgc](http://www.ornl.gov/ipgc)). 8.6X depth whole-genome shotgun data from *Populus trichocarpa* is now publicly available, completing the shotgun sequencing phase ([genome.jgi-psf.org/poplar0/poplar0.home.html](http://genome.jgi-psf.org/poplar0/poplar0.home.html)). The computational reconstruction of *Populus* genomic sequence suggests a whole genome size of ca. 485±10 Mb. Over 95% of the estimated 429 Mb of the euchromatic DNA is in the current assembly. The assembled genome has been reconstructed into large contigs and scaffolds, with typical size (N50) of 127 kb and 1.9 Mb, respectively. There are 58 scaffolds in the N50 count and 690 contigs. The genetic map and sequence assembly have been united using 691 mapped SSRs representing the 19 *Populus* chromosomes. These mapped SSRs occur on ca. 199 scaffolds and represent ca. 305 Mb of sequence. Single nucleotide polymorphisms occur 3 times in every 100 bases. Ninety-one percent of the publicly available *Populus* EST sequences (ca. 200,000 individual

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**Populus Sequencing at JGI**

*Nisqually-1 was sequenced clone: P. trichocarpa from Washington*

7.65 million sequence reads • 2.5-3.0 kb library: 4.4 million • 6.5-8.0 kb library: 2.6 million • 36 kb library: 0.65 million • Equivalent to 3100 reams of paper at 10 point font, or 250 file cabinet drawers • ~4.8 billion high-quality bases • 8.0X coverage of 480±10 Mb genome

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⁸ Genome Sciences Centre, 570 West 7th Ave., Vancouver, BC, Canada V5Z 4S6
sequences, forming ca. 11,885 unigene clusters and 12,759 singletons) were found in the assembled sequence and align at 85% identity over 50% of their length. A set of 2000 full-length cDNAs and 1112 full-length in silico cDNAs are being used to train three autonomous ab initio gene-calling algorithms: GRAIL-EXP, EUGENE and FgenesH. These algorithms have identified between 32,000 and 50,000 gene models in *Populus*. Of the 1112 in silico cDNA sequences, each over 1.0 kb, 95.0% showed a very high similarity (BLASTX score=200) to *Arabidopsis*. A conservative estimate gene order suggests that there are substantial regions of microcollinearity between the *Populus* and *Arabidopsis* genomes. Approximately 27% of DNA sequences from *Populus* BACs were homologous to protein-coding regions in *Arabidopsis*, and 46-58% of *Populus* gene pairs have pairwise homologs on a single *Arabidopsis* chromosome. In a BLAST comparison of the current *Populus* assembly with the *Medicago* BAC sequence database, we discovered that all 649 *Medicago* BACs had similarity to at least one *Populus* scaffold at E-10. In a preliminary analysis, involving seven of the *Populus* scaffolds, the *Medicago* BACs mapped to the same *Medicago* linkage group more frequently than expected by chance (Poisson P-value < 0.05).
Areas for Innovation

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Abstract

Poplar is widely accepted as the model tree for forest biology research. To more fully utilize its recently released genome sequence and to ensure rapid development of forest biotechnology, current technological gaps need to be filled.

Transgenesis is one of the main ways by which gene function is demonstrated. Currently, the efficiency with which transgenic lines can be produced from most poplar genotypes is too low to be of practical value for genomics research. To make significant improvements, genes that affect regeneration need to be identified.

To date, plant genetic engineering has largely been performed using strong constitutive promoters. The production of transgenic plants altered in their expression of endogenes vital to growth and development will be impossible until a reliable system exists for conditional transgene expression. The availability of an inducible excision system is valuable for both applied and fundamental studies. This system will not only provide for the removal of selectable marker genes, but will also permit the utilization of some innovative transformation schemes.

Federal regulators have implied that it will be necessary to develop a system for mitigating the spread of transgenes in the environment before genetically engineered trees can be deployed commercially. This requirement will likely be satisfied by modifying floral development. Long juvenile periods have been a serious impediment to researchers working in this area. In order to make more rapid progress, an early-flowering genotype or a simple, reliable method of floral induction is needed.

Finally, a versatile system for long-term storage of germplasm is essential. Cryopreservation is viewed by many as the only viable method for storage and distribution of important genetic stocks.

Background

Poplar (genus *Populus*) is widely accepted as the model tree for forest biology owing to its small genome, increasing genomic resources, rapid growth, and the relative ease with which it can be clonally propagated *ex vitro* and transformed and regenerated *in vitro* (Bradshaw *et al.*, 2000; Wullschleger *et al.*, 2002). International efforts are underway by groups from Canada, Sweden, France, and the U.S. to expand its available resources, including genetic/QTL mapping, expressed-sequence tag (EST) databases, microarrays, protein profiling, and single nucleotide polymorphism (SNP) discovery. Genome Canada has invested over $10 million to develop genomics tools for poplar and spruce, including 200,000 ESTs; 130,000 SNPs; BAC fingerprinting; and EST-based microarrays. In Sweden, approximately 100,000 target ESTs have been
sequenced, and a microarray of 25,000 unique ESTs has been established. Finally, the U.S. Department of Energy recently released an 8.1X draft genome sequence for *Populus trichocarpa* (bahama.jgi-psf.org/prod/bin/poplus/home.populus.cgi). To more fully exploit the poplar genome sequence and to help ensure more rapid development of forest biotechnology, current knowledge and technology gaps need to be filled. Although the focus of this chapter will be on poplar, much of this information is equally applicable to other tree species.

### The Wish List

#### Transformation

Two processes are needed to genetically engineer a plant. The first, transformation, requires stably integrating DNA into the chromosome of an individual plant cell. The second process, regeneration, involves coaxing individual transformed cells, through hormonal and cultural manipulations, to develop into a whole plant. Although the two procedures are distinct, they are often collectively referred to as “transformation.” Generally, regeneration is the more limiting of the two.

Plant transformation has historically been performed to introduce heterologous, commercially desirable, single-gene traits, such as insect resistance or herbicide tolerance. To date, there has been an emphasis on genes not available from sexually compatible species. Transgenesis is increasingly being used to identify native plant genes that may be of value for both basic and applied research. Once isolated, those candidate genes must then be ectopically expressed to confirm functionality.

While reliable transformation systems have been developed for pure species and hybrids of poplar in the section *Populus*, the genotypes in other sections have proven recalcitrant. To date, only a limited number of genotypes in sections *Tacamahaca* and *Aigeros* have been successfully transformed (e.g., Confalonieri et al., 1994, 1995; DeBlock, 1990; Heuchelin et al., 1997; Huang, 1994; Wang et al., 1996), and efficiencies are still too low for effective use of large-scale gene discovery techniques. This is certainly true for the *Populus trichocarpa* genotype that has been sequenced, Nisqually-1 (section *Tacamahaca*), which has been very resistant to regeneration. Efforts have recently been made to improve its transformation efficiency (e.g., Ma et al., 2004), but further improvements are needed to increase the utility of this genotype. Regardless of the section, the most commercially and experimentally important genotypes tend to be the most difficult to regenerate.

The efficiency with which we can produce transgenic poplar lines varies greatly among genotypes, from less than 1% to greater than 30%.

Transformation protocols are typically optimized for a single genotype, using complex, labor-intensive, complete-factorial experiments. A more universal protocol has not been developed because we lack a fundamental understanding of how plant cells acquire the competence to regenerate *in vitro*. Using rapidly advancing genomics tools, it is now possible to unravel this
conundrum. The research community will soon have access to a chip on which sequence information for all poplar genes has been spotted. Using this microarray, it will be possible to identify genes that interfere with or promote regeneration by evaluating expression levels for all genes in tissues that differ in their regeneration potential, before and after being induced to regenerate. In addition, gene expression profiling that is done on tissues gathered during the juvenility-to-maturity transition could help identify genes affecting regeneration, similar to the approach described by Brunner and Nilsson (2004) to identify genes involved in flowering control. Some of this research has already been conducted by industrial scientists, but the information resulting from this type of work needs to be in the public domain.

Finally, an attempt should be made to produce an in planta transformation method similar to the one established for Arabidopsis (Bent, 2000). Not only does this provide potential as a more efficient transformation system, but also the rapidity with which transformants can be produced through this approach should lower the risk of somaclonal variation, which can result from the use of more traditional methods.

**Promoters**

Plant genetic engineering has largely been performed using strong constitutive promoters (e.g., 35S from cauliflower mosaic virus), the aim being to obtain maximum expression levels throughout the plant. Such a strategy may be useful when introducing heterologous genes that impart certain commercial traits (e.g., insect resistance or herbicide tolerance), but may not be practical when the goal is to alter the expression of an endogene in order to demonstrate functionality. Using transgenesis for large-scale evaluation of gene function often requires the production of transformants altered in their expression of genes vital to growth and development. Constitutive expression of these genes may be lethal or have otherwise undesirable consequences for the plant.

Thus, there is growing demand for reliable systems that allow for conditional transgene expression. These could include tissue- and temporal-specific promoters, such as those active during various stages of wood formation or floral development, as well as inducible promoters. Systems have been developed to be responsive to a variety of inductive agents, including copper, ethanol, dexamethasone, estradiol, herbicide safeners, tetracycline, the inducer of pathogen-related proteins, benzothiadiazol, and the insecticide methoxyfenozide (reviewed by Padidam, 2003). It will be necessary to test the toxicity, inducibility, and specificity of each inductive agent, as well as determine the level and locality of expression for plants in which it will be used.

To determine its utility in poplar research, Mohamed et al. (2001) have studied a copper-inducible gene expression system first demonstrated in transgenic tobacco (Mett et al., 1993). The system comprises a constitutively expressed, copper-activated transcription factor (ACE1), together with a hybrid promoter containing an ACE1 binding site (MRE) and the –90 fragment of the 35S promoter, both driving expression of the GUS reporter gene. Unexpectedly, GUS expression occurs at high levels in the absence of the ACE1 gene in transgenic plants. Therefore, the system does not appear to provide useful copper-inducibility in poplar, possibly due to an endogenous factor that interacts with ACE1. This
experience illustrates the importance of testing systems in poplar that initially have been de-
vised for other species (e.g., Arabidopsis).

Selection
During transformation, a selectable marker gene is physically linked to the gene of interest. This marker gene is often one that imparts resistance to an antibiotic or herbicide. As a result, a transformed cell can be isolated on a medium containing the appropriate selection agent. While this method is convenient, it is often problematic. First, performing subsequent rounds of transformation may not be possible because only a limited number of selectable marker genes are available. Second, various selection agents can have dramatic and negative effects on regeneration. Finally, the presence of a selectable marker gene is usually an impediment to gaining public acceptance of genetically engineered plants.

Recently, alternative selection systems have been developed. These are based on a growth me-
dium that lacks a substance needed for proper metabolic activity or physiological development. A particularly attractive option exploits the inability of a cell to regenerate a whole plant without the addition of a phytohormone, or its derivative, to the culture medium at a precise step in the regeneration process. For example, most plant transformation protocols rely on the addition of cytokinin to a medium that induces the differentiation of adventitious shoots or em-
bryos from transgenic calli. The β-glucuronidase gene (GUS), a common reporter, encodes an enzyme that cleaves glucuronide residues. The glucuronide derivative of benzyladenine is bio-
logically inactive; if it is the sole cytokinin incorporated in the induction medium, regeneration cannot occur. However, upon hydrolysis by GUS, a biologically active cytokinin is liberated to induce regeneration. This supplement must necessarily be transitory because cytokinin can inhi-
bite subsequent root development.

Another positive selection strategy involves inserting a gene whose product imparts a metabolic advantage to the transformed cell. Mannose is a sugar that plants are unable to metabolize; cells starve when grown on a medium containing mannose as the sole carbon source. When taken up by the cells, this sugar is phosphorylated by a native hexokinase. However, plants lack a na-
tive phosphomannose isomerase gene, which encodes an enzyme that catalyzes the conversion of mannose to a useable six-carbon sugar (Joersbo et al., 1998). Similarly, xylose isomerase, anoth-
er enzyme that plants lack, is able to convert xylose to a sugar that can be utilized (Haldrup et al., 1998). Regeneration protocols that exploit positive selection strategies such as these are up to 10-fold more efficient than those that rely on more traditional, negative selections.

Excision Systems
The ability to reliably delete unwanted pieces of DNA is a valuable tool for both basic and ap-
plied research. For example, such methods permit the removal of selectable marker genes to both alleviate public concern and allow for easy retransformation using vectors derived from a common backbone. Moreover, some alternative regeneration systems (e.g., MAT -- see below) depend on excision for their success. Because transposons have proven too unreliable, alterna-
tive systems, such as Cre/lox (Russell et al., 1992), FLP/FRT (Lyznik et al., 1996), and R/RS (Onouchi et al., 1995), have been exploited. Gene excision vectors typically include: 1) a re-
combinase gene, usually under the control of an inducible promoter, and 2) recognition sites that flank the DNA targeted for removal. However, these systems are differentially effective, if at all, in various plants. Thus, it is necessary to determine which is the most appropriate for use with poplar and other tree species. For each system, one must ascertain the efficacy of the recombina-
se and how cleanly it excises the target. In addition, it is important to have a de-
pendable inducible promoter (as described above).
Producing Marker-free Plants

To produce marker-free plants, the primary transformants, which contain an antibiotic resistance gene bordered by recombinase recognition sites and linked to the gene of interest, generally must be retransformed with a gene encoding the appropriate recombinase. Secondary transformants must then be bred to segregate the recombinase gene away from the gene of interest, which is left behind after recombination. However, Gleave et al. (1999) have described a technique to recover marker-free plants without mating. Their primary transformants have a T-DNA insert containing the cytosine deaminase gene (\textit{codA}) linked to the neomycin phosphotransferase gene (\textit{NPTII}), which imparts resistance to the antibiotic kanamycin. The \textit{codA} gene product converts 5-fluorocytosine (5-fc) to 5-fluorouracil, which is toxic to plant cells. Both marker genes are bordered by \textit{lox} sites for excision; removal of \textit{codA} allows for tolerance to 5-fc. An attempt has been made to retransform primary transformants with the \textit{Cre} gene, the product of which is a recombinase that recognizes the \textit{lox} sites. Surprisingly, 50% of the lines regenerated following the second round of transformation are devoid of a transgene of any type (\textit{codA}, \textit{NPTII}, or \textit{Cre}). Although the T-DNA bearing \textit{Cre} is not integrated, transient expression is sufficient to cause excision of the other two genes. It has been shown that T-DNA transfer and the expression of genes therefrom occur at a high frequency, and that T-DNA integration into the genome is often what limits recovery of stably transformed plants (Narasimhulu et al., 1996).

The newly developed multi-autonomous transformation system (MAT) allows for the production of transgenic plants lacking selectable marker genes from a variety of species (e.g., tobacco, aspen, rice, snapdragon) (Ebinuma and Komamine, 2001). These vectors harbor \textit{Agrobacterium} genes (\textit{ipt} or \textit{rol}) that control sensitivity to or the biosynthesis of phytohormones. Cells transformed with these vectors regenerate into plants with either a “shooty” or “hairy-root” phenotype. MAT vectors also contain a site-specific recombinase for excision of both the recombinase and the oncogenes. The excision system consists of a recombinase gene, often under the control of an inducible promoter, and recognition sites flanking the DNA fragment to be removed. This alternative production system is attractive because it: 1) has the potential to increase both the yield and speed with which transgenic plants can be produced, facilitating the use of various high-throughput strategies, and 2) may eliminate the need for specific selection and regeneration conditions, making it possible to transform a wider array of genotypes.

Mitigating Transgene Spread

The Animal and Plant Health Inspection Service (APHIS) is currently revising its Coordinated Framework so consideration can be given to transgenic woody perennials. It seems likely that before genetically engineered trees can be deployed commercially, a method to mitigate the risk of transgene spread in the environment will be needed. [Regardless of what the federal regulators require, incorporating a transgene confinement system into transgenic trees is the right thing to do, at least initially, from the perspective of public perceptions.] Many researchers are investigating ways to modify floral development to satisfy this need. The two most common approaches are to engineer trees that are either reproductively sterile or have delayed flowering. The latter may be useful for short-rotation intensive culture (SRIC), where trees are harvested before the onset of maturation. The main techniques being employed to engineer sterility are: 1) cell ablation (floral-specific expression of a cytotoxin); 2) RNA interference (silencing native genes via short, interfering RNAs)Fig. 1; and 3) dominant nega-
viable mutations (DNMs) Fig. 2 that lead to the production of a dysfunctional version of a gene product, such as a transcription factor (reviewed by Meilan et al., 2001).

Because of functional redundancy, suppression of more than one floral regulatory gene is likely to be needed to achieve complete sterility. Where redundancy is clear, RNAi constructs can be designed to effectively silence several members of a multi-gene family (Waterhouse and Helliwell, 2003). It is also advisable to utilize multiple mechanisms that affect the expression of genes in more than one family to increase the likelihood of developing a successful confinement strategy. Transgene expression has been shown to be unstable under a variety of conditions (Brandle et al., 1995; Köhne et al., 1998; Metz et al., 1997; Neumann et al., 1997; Scorza et al., 2001). Therefore, it will be necessary to conduct multi-year field studies, in a variety of environments, and after the onset of maturity, in order to ensure durability of a given confinement system.

Progress in this area has been hampered by the inherent long juvenility of trees. Even the five- to seven-year juvenile period for poplar is a serious impediment. Although it has recently been reported that a genotype of *Populus alba* (6K10) can be induced to flower precociously, its practical use is limited. The induction regime is lengthy and complex, and specialized equipment is required. In addition, not every plant in a population responds to induction. Moreover, the efficiency with which the genotype can be transformed is very low (Meilan et al., 2004). Because 1) both male and female sterility will be needed, 2) poplar is dioecious, and 3) 6K10 is a female, any confinement system would need to be tested in another poplar genotype. Early-flowering genotypes are rare and poplars, in general, do not respond well to treatments that have induced precocious flowering in other woody angiosperms (Meilan, 1997). Thus, there is a demand for alternative genotypes that can be reliably and efficiently induced to flower early.
Cryopreservation

Finally, a versatile system for long-term storage of poplar genotypes is critically needed. Plant preservation has traditionally relied on seed banks or collections in gardens, orchards, or clone banks. Seed storage is the most common mode for many angiosperms and gymnosperms, but for species with long generation times, actively growing samples are the preferred form of preservation. However, maintenance of actively growing collections is labor-, time- and space-consuming, not to mention dealing with the risks of pest infestations and microbial contamination. In addition, plants or tissues maintained ex vitro or in vitro are subject to growth constraints and environmental fluctuations that can reduce viability and inhibit propagation potential. Field-planting transgenic trees for long-term preservation suffers from the additional burden of regulatory constraints, ecological and security concerns, and difficulties in maintaining juvenility. Cryopreservation is viewed by many as the only reasonable method for long-term storage and distribution of important germplasm stocks.

It is vital to develop and test cryopreservation protocols that enable stocks to be stored at low cost and with minimal rates of somaclonal variation. Vitrification is a simplified cryostorage procedure that eliminates the need for expensive cooling devices. It relies on the controlled application of cryoprotective solutions that desiccate and penetrate cells at low temperatures, leading to increased viscosity of the cytosol and formation of an immobilized solution state. When vitrification is optimally achieved, even the most delicate tissues can survive direct immersion and storage in liquid nitrogen without ice-crystal damage. Because of its simplicity and low cost, vitrification has become a preferred cryostorage method (Tsai and Hubscher, 2004).
Conclusions

Poplar is the third plant species for which the entire genome sequence is now available. It can serve as a versatile model system for understanding the fundamental aspects of tree growth and development. Because of its phylogenetic relationship to Arabidopsis, there will be unique opportunities for conducting research on comparative developmental biology. However, to more fully exploit the quickly emerging genomic resources and to help ensure more rapid development of forest biotechnology, certain knowledge and technology gaps described herein must be bridged.

Literature Cited


What is Needed? Barriers, Issues and Perspectives

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The Societal Interface: It has been 17 years since the production of the first transgenic tree, an herbicide resistant poplar; yet transgenic trees have not become part of production forestry in the western world. The primary barriers to progress are philosophical and political. The deployment of transgenics in China may change perspectives. To address philosophical concerns of transgenic trees, one strategy is to develop plants to solve socially beneficial non-market driven problems such as restoration of extinct or threatened species or ecosystems (the American chestnut paradigm) or landscape bioremediation and restoration using transgenics. Technical barriers remain regarding the ability to transform desired species and specific genotypes.

What do you do after you finish the genome sequence? Genome sequences will be extraordinary resources that will dominate tree genetics, however, it is an exceedingly challenging problem to determine how such information can guide and inform tree breeding and genetic engineering. Poplar will become a greater focus of interest because of complete genome sequence of *Populus trichocarpa*, which will be largely completed in the next year. Sequence information for *Eucalyptus camadulensis* is anticipated in 2006. The primary reason for genome sequence is the definition of all the genes and their locations. However, we lack a general and effective definition of what is a gene, so deciding what we have is still a problem. In addition, methods used for sequencing typical plant and animal genomes are not yet adequate for large conifer genomes such as pine and spruce. Partial genome information will still be useful, and it may be a long time before full genome information is obtained.

Association Genomics: Association of genotype and phenotype. What genes are involved in the determination of important traits, or superior performance in forest trees? Quantitative genetics can be used to associate traits and genome location using QTL analysis. Gene sequence variation such as SNPs can be associated with quantitative phenotypes, and variation in gene specific transcript level may also be correlated with quantitative traits. The combination of these types of quantitative analysis should become more powerful as technology improves. In addition, quantitative analysis of metabolites, on a population level, will provide a new level of inference and support results from SNPs and transcripts.

Major Gaps: Knowledge gaps exist regarding the extent and mechanisms of epigenetic regulation of genes and genomes (epigenomics). There are major technical gaps in sequencing, microarrays, proteomics, metabolite fractionation, mass spectrometry, NMR, MRI, and many other methods. All could be improved by an order of magnitude in resolution and throughput and still not saturate the need for information.

Integrating Everything:
Integrating genomics, proteomics, metabolomics and studying interactions of components is often called a systems biology approach. It will also be necessary to integrate quantitative genetics, population genetics and evolutionary biology to understand the relationships of single traits and single genes. Such information is just beginning to arrive, producing challenges for bioinformatics on an increasingly greater scale.

Integrating New Technology and Standard Processes

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Biotechnology can be divided into the general categories of: 1) genetic transformation, 2) genomics, 3) vegetative propagation, and 4) marker applications. Each of these biotechnology tools can be applied to various interest areas including, but not limited to: 1) biodiversity, 2) conservation, 3) forensics, 4) genealogy, 5) pests, and 6)
One of the greatest gaps lies in integrating these technologies with processes that scientists and managers can use and that they value.

productivity. All of these interest areas find some application in understanding and management of forest resources, both plant and animal.

One area that is crucial for a breakthrough application in forestry is sterility in transgenic trees. The public will demand it before these trees are able to be planted in any significant quantity. In addition, ecological concerns in general will warrant it. Some work is already underway in this field, but more emphasis should be placed on it because without it forestry with transgenic trees will remain a dream.

New technologies in biotechnology are being developed very rapidly; and in a sense, applications are not keeping pace. One of the greatest gaps lies in integrating these technologies with processes that scientists and managers can use and that they value. For example, genetic transformation has been demonstrated for many tree species; yet the number of traits of economic interest amenable to transformation is very limited (e.g., Bt genes, some herbicide resistance genes, and genes for some wood properties). Now that the technology is relatively reliable, serious discussions need to be conducted between geneticists and managers as to the traits of economic interest.

In addition, biotechnology tools should be integrated into existing long term programs. Genetic transformation should focus on the best pedigreed genotypes, if available, to create value added. Efficient clonal technology is a must for best utilization of biotechnology techniques; but it should be part of a population of clones; not just one or two. Molecular marker applications should be emphasized and partnered with top quality tree improvement programs to be part of population improvement. There is little value in forestry of having a single, albeit highly valuable, clone. Given the long term nature of forests, genetic diversity is mandatory for traits that condition fitness (e.g., survival, ability to withstand competition, etc.) even though genetic variation is narrowed for growth and productivity traits that are under selection. A holistic tree improvement strategy must be developed that includes biotechnology tools. It is easy to become enamored with the science but it is mandatory that applications are developed. This in fact is the long term work that is needed.

New technologies in biotechnology are being developed very rapidly; and in a sense, applications are not keeping pace.

A genomics approach to describing and understanding the genetic and molecular basis of all biological processes controlling economically and ecologically relevant traits in pine is both feasible and desirable. Excellent progress in gene discovery, marker development and QTL mapping has been made in loblolly pine and near-term breakthroughs in functional genomics and physical mapping are anticipated. Furthermore, pine is ideal for conducting association genetic studies; current efforts in this area are among the most progressive in the plant genomics community. Trees possess an abundance of natural variation that makes the potential for tree improvement large, but progress using traditional means slow. Few, if any, crops would benefit more from the development of genomic technologies that enhance our understanding of biological processes.

Support for genomics research in conifers has lagged significantly behind most major agricultural crops and model species. Initiatives are required

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from the pine genomics community and those who would benefit from that research (public and private land managers/owners, forest, paper, and energy industries) to enhance research support and speed progress. An ad-hoc group of scientists (Loblolly Pine Genome Project) have met twice to identify the current status of genomics research in loblolly pine and significant knowledge gaps that need to be filled (dendrome.ucdavis.edu/lpgp/pdf/LPGP_2004.pdf). It is anticipated this information will a) help guide and prioritize future R&D proposals, b) help scientists identify useful research collaborations, and c) provide rationale and background to improve funding efforts. Generally speaking, the LPGP seeks to find and identify all or most of the genes and regulatory elements in the pine genome, characterize the genetic variation in them through DNA sequence analysis, and, finally, determine the relationship between that genotypic variation and expressed plant phenotypic variation. In particular, additional knowledge and/or technology development is required for:

- **Gene Discovery**: Enhanced EST, BAC and COT libraries
- **Gene Identification**: Enhanced gene expression platforms and unigene sets; publicly available pine transformation systems, and supported community-wide database management infrastructure.
- **Gene Characterization**: Identify and map 35K SNPs representing a loblolly pine unigene set; place 1K SSRs on a reference map; construct a physical map and integrate with genetic map.
- **Associate Genotypes and Phenotypes**: Develop one or more public association genetic populations; develop high-throughput, inexpensive SNP genotyping and phenotyping methods; develop improved computation approaches for identifying associations.

The overall benefit of the application of genomics to loblolly pine will be a vastly improved understanding of the biological and molecular basis of adaptive and economic traits of the most dominant genus of forest trees in the world and significantly improved precision of genetic improvement practices that will surely reduce the time and cost of these activities.

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1 There are over 110 species of pines and comparative genomics studies show they are remarkably similar, genetically.
What are the appropriate strategies for the future in research, development, and technology transfer in forest biotechnology as well as addressing associated societal and regulatory issues?
Genomics and Tree Improvement

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1) Has biotechnology and genomics helped or hurt tree improvement?
This point was raised several times during the course of the symposium, as it is at most venues where breeders gather with molecular biologists to discuss the pros and cons of biotechnology and genomics.

It can be instructive to ask ourselves this — Would tree breeding programs have continued at full strength if biotechnology had not come along?
My contention is that Genomics and the other ‘omics’ are enabling and are resulting in an invigoration of traditional genetics programs in forestry and agriculture rather than supplanting them.

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Examples:

i. Cytogenetics was essentially dead but is now a vital research area because genomics created a need for it.

ii. University programs in quantitative genetics with plants were waning until QTL mapping came along. Now all of the mathematics-challenged molecular biologists (like me) want quantitative geneticists with field data to work with them on mapping.

iii. Population Genomics is a new field created because of genomics, involving large scale SNP / trait association studies. Forestry has always been strong in population genetics. Population genomics will allow us to efficiently access the huge reservoir of natural genetic variation in our large forests that previously was not readily available for use in tree breeding.

2) Is reorganization of the forest industry from vertically integrated to one divested of land ownership a problem for forest biotechnology or an opportunity?

The first large scale field trials should include tests of biological and physical confinement approaches using either marker genes or preferably genes of economic value that are considered safe.

My contention is that this may be an opportunity for us, as the companies owning the forest lands will be dependent on productivity for their profits, whereas the large integrated lumber and pulp and paper companies were not.

3) Large scale field tests of GE trees are needed now.

My contention is that if we are ever going to know how safe releases of GE trees are, we will need relevant field tests and the sooner the better.
However what products should be released first?
My contention is that the first large scale field trials should include tests of biological and physical confinement approaches using either marker genes or preferably genes of economic value that are considered safe. The latter would permit companies to benefit from the tests, and not need to wait another 15 years before deploying their first generation GE products, while also providing excellent data for use in evaluating future GE releases.

I presented the case for this approach in the National Research Council report “Biological Confinement of Genetically Engineered Organisms” by the Committee on the Biological Confinement of Genetically Engineered Organisms (Kirk et al., 2004, National Academies Press, Washington, DC, 284 pages) in which I participated. The report, the result of 18 months of work by the committee, can be downloaded at www.nap.edu/books/0309090857/html, or a hard copy purchased from the National Academies of Science.

Population genomics will allow us to efficiently access the huge reservoir of natural genetic variation in our large forests that previously was not readily available for use in tree breeding.
Forest Biotechnology and Conservation

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Conservation international has not historically had significant active programs on forest biotechnology. However, we have a strong interest in staying abreast of developments in research, technology, and policy, particularly as those developments may relate to our biodiversity conservation mission. This is a layperson’s view, from the perspective of someone actively engaged in collaborative efforts to achieve forest conservation and sustainable wood fiber production.

Threats to the world’s forests are especially acute in the tropics, where just 45% of original extent of habitat remains and the remainder are being lost at rate of 1% per year.

The world’s forests are under severe pressures from unsustainable logging and road building. The threats are especially acute in the tropics, where just 45% of original extent of habitat remains and the remainder are being lost at rate of 1% per year. Current rates of tropical deforestation are equivalent to an area half the size of Florida being removed from the lower 48 annually.

Of course commercial timber production is not the only contributing factor, since many other forces are driving the global forest crisis. But the infrastructure associated with timber extraction is often at the vanguard of habitat conversion and threats to endangered species.

A compelling example was published recently in Nature: gorilla and chimp populations in Gabon and the Democratic Republic of the Congo dropped by 80% from 1983-2000, leading scientists to recommend immediate designation of the species as “critically endangered.” The decline was attributable to illegal bushmeat hunting and Ebola virus epidemic, but a significant root cause was expansion of new a logging road network into remaining intact tropical forests in western equatorial Africa.

Trends in the tropics are highly relevant to the future of forests and the forest and paper industry in North America. A new report commissioned by AFPA and conducted by Seneca Creek Associates found that illegal logging – mostly but not entirely in the tropics – significantly depresses U.S. and world prices for wood products.

Tropical deforestation accounts for 20% of the greenhouse gas emissions responsible for global warming and the threat of climate instability. Global warming, in turn, presents enormous risks to the world’s biodiversity. Research findings published earlier this year in Nature estimated that one-third of all species could be committed to extinction under current global warming scenarios as a consequence of disruption of habitat ranges and other results of changing climate patterns.

Moreover, forest destruction is a major driver of loss of terrestrial and freshwater resources that provide essential ecosystem services for humanity and critical habitat for endangered species around the world. For instance, the global amphibian assessment recently published by CI, IUCN and Nature reserve concluded that more than 40% of salamanders, frogs, toads and other amphibians are in decline, with habitat loss as the major driver underlying this threat.

Fortunately, ingredients exist for convergence of interests between the business world, conservation community and the world’s consumers. A recent report by WWF — International titled “The Forest Industry in the 21st Century” concluded that meeting projected increases in global wood demand over the next five decades will not require significant expansion of commercial logging beyond the estimated 600 million hectares of timber lands that currently account for 90% of the world’s industrial wood supply.

A broad consensus may be emerging around the elements of a strategy that produces benefits for industry, communities and biodiversity. One element of the strategy is a shift away from commercial logging and road construction in biodiversity hotspots and major tropical wilderness areas. Another critical need is to secure and expand protected areas around the world. An additional component is to achieve best environmental practices on existing plantations, without tapping substantial new areas of natural forest for fiber production. The strategy must also include efforts to build international pressure on “bad actors”...
Intensive forestry or biotechnology should not be oversold as a panacea in the absence of concerted efforts by governments and the private sector to expand protected areas, stabilize and rebuild populations of endangered species, and create conservation corridors that combine protection of key biodiversity areas with ecologically compatible economic uses across the larger landscape.

conducting egregious logging, and strengthen enforcement systems to crack down on illegal timber.

What are appropriate strategies for the future in research, development, and technology transfer in forest biotechnology as well as addressing associated societal and regulatory issues?

A general answer is that the R & D strategy should be focused on whether and how forest biotechnology might contribute to achieving the objectives of conserving threatened forests and biodiversity while meeting society’s needs for forest products.

For example, does forest biotechnology have potential to enhance fiber production, while enabling reduced chemical applications and improved water efficiency, on intensive plantations established on degraded agricultural lands?

On this point, it is important to recognize that intensified timber management on existing plantations, while clearly a preferable alternative to liquidating remaining tropical forests, does not unto itself guarantee positive results for conservation. Intensive forestry or biotechnology should not be oversold as a panacea in the absence of concerted efforts by governments and the private sector to expand protected areas, stabilize and rebuild populations of endangered species, and create conservation corridors that combine protection of key biodiversity areas with ecologically compatible economic uses across the larger landscape.

The research agenda should objectively examine the pros and cons of forest biotechnology in terms of biodiversity and the environment.

It is very much in the interest of industry and the research community to establish credible regulatory structures at the national and international levels. We need to account for risk in carefully structured, transparent, and independent regulatory frameworks.

From a policy standpoint, failure to be fully engaged in international processes on biosafety may hurt the ability of the US to influence development of an international regulatory framework that would help create the necessary public confidence for biotechnology R & D to proceed.

Research on forest biotechnology is operating in a world where it seems public skepticism runs high and public acceptance remains low. The issue of GMO technology has become polarized and contentious, often to the point of making reasoned debate difficult. A number of voluntary programs operating in the marketplace have already incorporated restrictions on GMO technology in forest management and wood products, even prior to commercialization of biotechnology forest products. An example can be found in the principles and criteria of the Forest Stewardship Council certification program.

I believe that the research community and forest industry could take valuable lessons from the food and agriculture sector in recognizing that taking shortcuts on regulatory issues and public participation could result in lengthy delays or loss of valuable new technological innovations. The Institute of Forest Biotechnology is pointing the way for how to “do it right” rather than repeating past mistakes. The Institute is playing an incredibly valuable role, with conferences such as this one, that provide forums for setting a research agenda that is patient, deliberate, thorough and inclusive.

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Building a Successful Research Community

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Strong science is the key evaluation criterion for funding at NSF, and is also very important at other agencies. A variety of relevant criteria are used to assess the science quality and likely impact. These were discussed as a series of questions.

A federal funding agency likes to see that a community has come together and presents a common voice prior to asking for significant resources.

- How unique is the research problem? Why shouldn’t the problem be tackled using a simpler experimental system? This is especially relevant for tree biology.
- How will the work contribute to our overall understanding of biology? An impact beyond the specific community being targeted elevates a proposal compared with similarly meritorious ones. The sequencing of the first Populus genome is a great example.
- How will other scientists access your findings? This is especially important for projects that generate lots of data, only a small fraction of which will appear in publications. Make sure that you have adequate informatics support.
- Formal coordination with related projects is increasingly important. Make sure that you establish and document appropriate collaborations and sharing of data. With research dollars at a premium, the funding agency needs to ensure that there is maximal synergy and minimal overlap.

At NSF, broader impacts are critical and broadly defined. Some examples include documenting:

- How large is the community that will benefit and who are they? Do your homework up front and document the stakeholders. These can include industry, basic scientists, educators and others.
- What are the training needs of this community and how will the project impact these? It is especially important to document how your project will go beyond training pre- and post-docs.
- How will you reach out to the lay public? This is helpful but not required.

Large projects are different. A federal funding agency likes to see that a community has come together and presents a common voice prior to asking for significant resources. Communication is the key here.

Meet to discuss needs and create a unified plan (broad stakeholder representation is crucial).

- Do your homework before the meeting. Spirited debate is great, but I urge you to avoid public animosity.
- Ask for funding to support the meeting.
- Invite funding agency people as observers.
- Put together a white paper and send it to stakeholders.
- Buy-in from downstream industry is crucial. There are many ways to show support:
  1. Participation (leadership);
  2. Seed funding, in kind contribution, collaboration.

The tree biotech community appears to be in a terrific position with regard to industry — public sector communication and collaboration; you should play to this strength.

Model organisms have an important role to play in tree genetics and genomics. By definition they are simpler and more tractable than other species. Also, translational biology is becoming simpler in the ‘post-genome era’, so it becomes easier to leverage knowledge of models in economically important plants. This community has a good start with the completion of the first tree genome. Is there a master plan for cornerstone species to sequence over the next three to five years? What about functional genomics platforms for these species? Are you fully utilizing existing models (plants and microbes)?

As you think about conifer structural and functional genomics, I urge you to follow the example of the Solanaceae community and plan your strategy to have the broadest impact as possible. For example, they chose tomato as the first species to fully sequence for very good scientific reasons, but have organized to make maximal use of this species for the many other plants in the family and in related families.
New Century, New Trees

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