TREE BIOTECHNOLOGY
IN THE NEW MILLENNIUM

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International Symposium on Ecological and Societal Aspects of Transgenic Plantations

Editors: Steven H. Strauss, Oregon State University and
H.D. (Toby) Bradshaw, University of Washington

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Columbia River Gorge
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OREGON STATE UNIVERSITY

Natural Resources Canada
Canadian Forest Service

Proceedings of the First International Symposium on Ecological and Societal Aspects of Transgenic Plantations

In Conjunction with the IUFRO Conference on Tree Biotechnology in the New Millennium

July 22–24, 2001

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Skamania Lodge, Columbia River Gorge, Stevenson, Washington, USA

See the IUFRO meeting web site, to download a copy of this
proceedings, and to view all poster and paper abstracts:
http://www.fsl.orst.edu/tgerc/iufro2001/

PREFACE

More than 200 economists, ecologists, environmentalists, ethicists, molecular biologists, industry representatives, and government regulators from 23 countries convened at Skamania Lodge, along the scenic Columbia River Gorge between Washington and Oregon, for a 2-day symposium on the ecological and societal aspects of transgenic forest plantations (http://www.fsl.orst.edu/tgerc/iufro2001/eco_symp_iufro.htm). Of the 28 invited lectures given at the symposium, 14 were from scholars who presented a broad environmental, ecological, or ethical view. The symposium was held in conjunction with the biennial meeting (22–27 July 2001) of the International Union of Forestry Research Organizations Unit on the Molecular Biology of Forest Trees (Vienna, Austria: http://iufro.boku.ac.at/). This proceedings attempts to capture the main issues raised in the lectures, breakout sessions, and summary statements. Among the widely accepted conclusions from the conference are the following:

- A great deal more scientific research is the most glaring need to help answer questions of benefit and safety, and thus of social acceptability. The question of "do we really need it?" cannot be answered until much more is learned from laboratory and field research.
- Plantation forests have the potential to concentrate industrial wood production on a small land base, and thus spare wild forests from intensive harvest. Whether this actually occurs depends on social mechanisms for protection as well as on technological innovation.
- The long lifespan of trees, and the common presence of wild or feral relatives, are particularly troublesome for benefit/safety assessment, which is therefore likely to require a combination of modeling, monitoring, and adaptive management. Genetically engineered flowering control was considered critical for some traits to restrict transgene dispersal. However, the notion that trees engineered with one or a few genes are functionally analogous to exotic invasive organisms, and thus are likely to "threaten" wild forests, was widely rejected.
- Research to date has demonstrated a high degree of health and stability of performance of genetically engineered trees in field trials oriented toward possible commercial applications.
- None of the attendees called for a moratorium on all field research with genetically engineered trees, as Greenpeace has demanded. But Faith Campbell (American Lands Alliance) and Sue Mayer (GeneWatch UK) called for a moratorium on the commercial release of genetically engineered trees until further research indicates that large-scale plantings would be environmentally safe.
- Participants expressed a high level of optimism about the potential for research to enable beneficial applications of GM trees. A survey taken at the end of the meeting (Appendix 1) revealed that 88% agreed or strongly agreed with the statement "Sufficient basic and applied research upon the genetic stability and ecosystem behavior of GM trees, and upon the design of biological safety mechanisms, can create environmentally safe and societally beneficial trees and outcomes."

This was the first international symposium to attempt to forge a consensus on how to move forward in research and public debate. It is abundantly clear that substantial progress was made in many directions, however it is also clear that many additional steps will be needed for the potential benefits and acceptability of genetic engineering in forestry to be fully explored.

H.D. Bradshaw, Jr. and Steven H. Strauss, 13 November 2001

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Welcome to EcoSocial and Molecular Biology Symposia

Steve Strauss

Dear Colleagues,

On behalf of my co-organizer Toby Bradshaw, my associates at Oregon State University, and the staff of the conference office at the College of Forestry at OSU, I want to officially welcome all of you to this conference. We have been planning it for two years, from logistics, to complex issues of scientific coverage and speaker selections, to obtaining grant and sponsor support to make it possible. It has been an amazing labor of love. This is by far the biggest party we have ever thrown.

My sincere thanks to the many sponsors who have made it possible, which in addition to those listed at the front of our binders, include CSIRO Australia and some others who, for fear of terrorism, elected not to have their names listed. What a pity that in this great democracy we live in, an organization feels that it cannot support an open scientific conference without retribution. While we welcome peaceful protests, like the one we witnessed earlier today, there is no place or need for violence in the already vigorous world debate on biotechnology.

It may be a big party, but it will also be the most demanding and exhausting party I have ever attended. The first two days, starting this evening with our keynote lecture, will be an intensive and controversial journey, as we explore the many and diverse ecological and social issues that surround genetic engineering in forestry. We will need to listen carefully not only to the technical views, but to the ethical and personal attitudes that underlie them. This will be a great challenge for all of us, and with the strong media presence here, I can tell you that the world is watching. Luckily, we have a brilliant, thoughtful, and responsible set of speakers to help guide us.

Then with little break, we will begin the hard biotechnology science, which will continue all day in close succession, including two concurrent evening sessions, through mid-day Friday. As always, this is complex stuff—even for us experts. Please pace yourself. However, we are fortunate to have a truly outstanding slate of scholars that it is no stretch to say represent the best that the science of forest biotechnology has to offer anywhere on planet Earth.

Also note that there is a survey in the front binder. We will ask you to fill this out, on the associated electronically scored sheet, at the end of the EcoSocial symposium. Please wait until then so you will have had the benefit of the symposium to inform you. This will help us to record the views of the attendees with respect to a number of issues.

Finally, I want to thank all of the attendees for making this conference a priority in their professional and personal lives. As many of you have pointed out, the cost is by no means insignificant. The time away from your families is always hard. And many of you have traveled across many time zones to get here. The great turnout—by far the highest yet for an IUFRO forest biotechnology meeting—shows that the agenda of topics and speakers are of interest to many.

I would now like to introduce my colleague and co-organizer Toby Bradshaw, who many of you know well. He will introduce our keynote speaker. Toby is a professor at the University of Washington in nearby Seattle, and has conducted pioneering studies on the genes that control adaptive traits in plants, including poplars, for many years.

Introduction of Keynote Speaker

Toby Bradshaw

It is my privilege tonight to introduce the keynote speaker, Dr. Hal Salwasser, from Oregon State University. Hal is the Dean of the College of Forestry at Oregon State, as well as the Director of the Forest Research Laboratory there. Hal came to OSU from a career at the U.S. Forest Service, where his last post was as the Director of the Pacific Southwest Research Station at Berkeley, California. He was the first person to hold the Boone and Crockett Endowed Professorship at the University of Montana, where his work on wildlife conservation is well known. His undergraduate work was done at Cal State-Fresno, and he received his PhD in Wildland Resource Science from Berkeley. Hal's talk tonight will be on the subject of future forests: environmental and social context for forest biotechnology.

Proceedings of the First International Symposium on Ecological and Societal Aspects of Transgenic Plantations, S.H. Strauss and H.D. Bradshaw, eds. College of Forestry, Oregon State University, 2001. pp. 10-19.
www.fsl.orst.edu/tgerc/iufro2001/eprocd.pdf

Keynote Address

Future Forests: Environmental and Social Contexts for Forest Biotechnologies

Hal Salwasser

It is a privilege to be asked to share some thoughts with a group of scholars and interested citizens on such an important topic as *Future Forests: Environmental and Social Contexts for Forest Biotechnologies.* Its significance is signaled by how many people have come from so many different countries to participate in the symposium. I am most pleased that two great public universities have hosted an open, public, scientific forum on such an important matter. This is the right thing for leading institutions of learning to do, to engage people with diverse perspectives and experiences to talk about, not just the science, but the social and ethical implications of biotechnology in general, and genetically modified organisms in particular.

To set the stage for this meeting, I am going share some perspectives on forests, forest management, forest conservation, and the role that biotechnology might play in future forests. I generally begin all of my presentations with a question, a fairly simple question: Why are we talking about this stuff anyway? I have a number of answers to that question, and I encourage you to think about why we should be talking about forests and biotechnology as well. The order of my answers will probably disclose some of my philosophical biases because these are in the order that I tend to think of them.

Fundamentally, we talk about forests because forest ecosystems are vital for life on earth. They form the headwaters of our major river systems. They sustain biological diversity and wildlife habitats in extraordinarily rich ecosystems. They are, obviously, the sources of wood, which is an environmentally superior raw material, when you stack it up against the other things that people might use as alternatives. For example, if we compare the energy and water use for building a 10 x 100 ft wall out of steel versus out of wood, we find that the wood wall uses much less energy and water than the steel wall. In addition to their environmental superiority, wood products meet many essential needs. Every day of our lives we encounter the benefits of wood. You can just look around this room and this marvelous hotel and get a first hand feel for that. Globally, wood is also an incredibly important material for energy. In some developing countries of the world as much as 70% of the energy for cooking and heating in rural areas still comes from wood.

There is also the role of wood in carbon sequestration. The best estimates I've been able to find show that about 40% of the carbon that is stored on the land is stored in forests or forest soils. Now, granted most of the carbon stored in the world is in the oceans, but forests are the big players on land. Forests also provide a multitude of recreational and spiritual values. Many of our cultures across the globe view forests as a major part of their identities. As an angler and a sometimes-hunter—and a sometimes-hiker, although not as often as my wife would like me to be—forests are an important part of my identity. So forests have all of these incredible values, and are just really remarkable places.

Fortunately, forests still cover a fairly large area of the land surface of the world, about a quarter globally, about a third here in the United States (Figure 1). Here in the Pacific Rim states, forest cover ranges from just under 40% in California to just about 50% up in Washington. Globally and in the United States, this is not as much forest as we used to have. That's because people transform forests through a wide variety of activities. This is not a recent occurrence. People have been transforming forests probably for as long as people have been around, at least for as long as they knew how to pick up a stick that had a fire burning on the end of it. Of these transformations, the most significant by far globally has been conversion of forests for agriculture and human dwellings. How we manage forests also transforms them. It typically does not change them from forests to something else, but it changes the character of the forests, their structure and composition. Examples of this are livestock grazing, recreation, and climate change—which of course, is a natural force of change, but the degree to which we've exacerbated climate change, that's a human effect. And I would encourage you to think about the degree to which water diversions and dams have transformed forests. We must have hundreds of thousands of hectares of riparian forests now sitting underneath reservoirs in the United States alone.

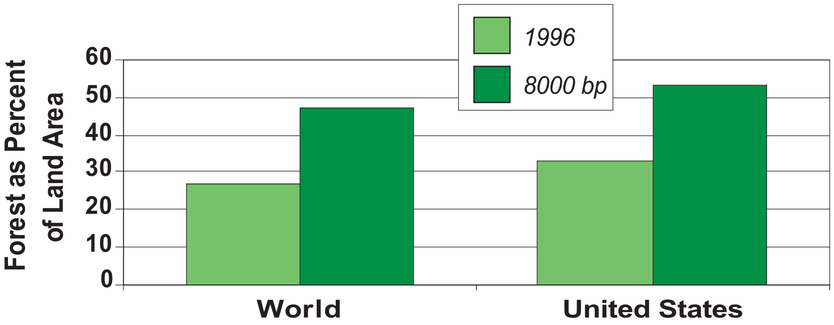

Figure 1. Forests cover a lot of land—but less than they used to. (Sources: World Resources 2000–2001; USDA FS RPA Assessment 2000.)

World population growth is the major force behind all this forest transformation, and we are still on a trajectory to increase our numbers by one-third to one-half by mid-century. So, we are not, by any means, free from the effects of human population growth. Some of the transformations that I've talked about tend to be relatively permanent, at least when we think of them in human lifetimes. Of course they are not permanent in geological times. Over very long periods of time, nature has a way of setting things back and erasing whatever imprint we're probably going to have. But we generally consider changes such as urban sprawl and agricultural transformations to be forest lost. Not all the transformations are losses though; forests are restored by a lot of the things that we do. We plant forests; sometimes we plant them back on abandoned agricultural lands. We certainly plant them back in places where we have harvested trees. To me, those kinds of transformation are net benefits to the environment.

Even though we can and do make beneficial changes in forests, there is still a problem: Globally, the losses are outstripping the gains. Since somewhere around the start of the agricultural revolution/industrial revolution, we've lost about 20%–50% of the original forested cover of the world. The 20% is an estimate on the low end, the 50% perhaps an estimate on the high end. It's very hard to be precise about this. During this same period, we've gained about 1000%

in numbers of people. So when you compare the losses and the gains, we end up with a lot less forest area per person to provide all of those benefits we expect out of forests: the water, the carbon sequestration, the wood, the biological diversity, the recreational access, the cultural identities, and so forth. That creates the future that we are heading into. We are going to have a smaller forested area, and we are going to expect it to serve more people. As those people gain in knowledge and affluence, they are going to expect the forest to serve them in more ways. We have seen a 40% increase in wood use in the last three decades. We are anticipating seeing at least a 20% increase in the next two decades. We've been on a fairly steady trajectory of about 1% increase in global wood use per year on average (Figure 2).

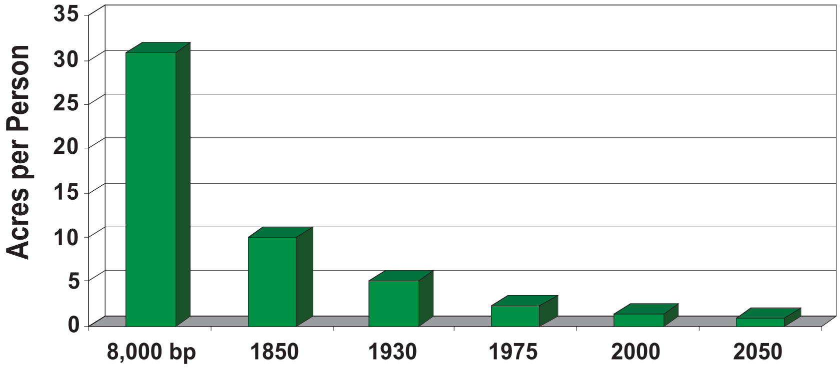

Figure 2. The amount of global forest per person has declined precipitously over the past 250 years. (Source: Source: World Resources 2000–2001, plus interpolations and projections.)

Meanwhile the demand for everything else we want from forests in addition to wood continues to grow. Water, I am convinced, is the ultimate resource of value to come from forests. When wars are fought over forest resources, they're going to be over water. We are seeing that happen in Oregon right now this year. Biological diversity conservation has also grown in importance over the last couple of decades and is now recognized as a major benefit that we expect from forests. But biodiversity is a very complex issue without universally clear strategies on how best to conserve it; too often protecting it in the short run in one place merely shifts human impacts to later dates or to other places. We are just on the verge of understanding the role of forests as carbon stores. We will eventually recognize that forests and wood held in permanent status and not burned up in some way are going to play a major role in carbon sequestration.

Now, the good news for future forests is that according to the best estimates—and some of those come from speakers here this week—we are within a decade or two of reaching a point at which approximately 40% of the industrial wood fiber produced in the world is going to come from planted forests. It is the hope and expectation of all foresters and conservationists that planted forests will relieve some of the pressure to take wood from native forests, at least in the developed part of the world.

An important part of my message in all this, is that forests can and will be sustained through management. Without management, our experience is that people either convert forests to some non-forest use or they over-run the forests. They over-run it with agriculture, or urban growth, or livestock grazing, or just harvest too much stuff, and the stuff ends up being not just the trees, but the plants and the forage and the wildlife and the water. With sustainable management, though, we have learned in many parts of the world that forests can be restored and can be protected. I don't want to have you perceive that I am saying that through management we can restore, and protect, and sustain the same kind of native forest that was there once upon a time before there were people, but we can still sustain and protect some pretty diverse, pretty productive forests. So, let's talk about what it will take to sustain forests for all their values and uses.

We, in the state of Oregon, have been blessed with some visionary leadership over the years. And just recently we experienced another pulse in that leadership. Our governor, John Kitzhaber, and our legislature just passed a new law that is called the Oregon Sustainability Act of 2001. That law recognizes sustainability as a goal for all programs of state agencies in Oregon, and adopts the Brundtland Commission and the United Nations definitions of sustainable development as the core goal. The governor added a few words about using, developing, and protecting resources, and then made sure that people understood that this is all done from the joint perspective of meeting environmental, economic, and community objectives. This is now the law and policy of the state of Oregon, and it gives us a tremendous new tool to work with.

Sustainability—this concept that is somewhat elusive, but big enough to provide a place for a lot of people to stand—is going to shape the future of forest management in Oregon, as it is in many other parts of the world. It already is shaping the forest management of today in many places, through both governmental programs and the programs of the marketplace and the private sector. It's going to focus on meeting both current and future needs, so it has intergenerational equity built into it. It seeks a balance between environmental protection, economic development, and the perpetuation of diverse and vital communities. So it has a good balance. It views people as part of nature and as part of ecosystems, not as a separate entity or as something to be dealt with after you figure out how to take care of the non-people parts. It forces us to consider all the forests in our decision, not just the ones in our own backyard. If done well, we hope it will enable us to keep forest ecosystems healthy and productive.

Sustainability is a concept that rests in a global context; it is not something we can accomplish at a local level just by focusing on local matters, not even if local means regional or national. Let me give you a couple of statistics here that illustrate why we must view forest sustainability in a global context. These percentages are accurate to within a few percentage points. I'm sure they vary from year to year, based on some market conditions. A year or so ago, I read a paper that said somewhere around 30%–35% of all the industrial wood—that's construction lumber, wood panels, furniture, paper, and packaging—that is consumed in the world has crossed at least one international border from the time it was a tree until the time it was used. One third of the world's wood products is moving across international boundaries. At least in recent years, the United States has imported between 35% and 40% of its softwood lumber from another country. Most of it comes from Canada, but increasingly it also comes from the southern hemisphere—from some of the fast-growing plantations in the southern hemisphere. More than wood is in the global marketplace. All over the world, we see forest enterprises that started out as local or regional companies expand to become national corporations and are now globally integrated corporations. Companies such as Weyerhaeuser in the United States, or UPM-Kymmene and Stora-Enso from Finland and Sweden. You used to be able to name the country that housed these firms, but no longer. They are not just U.S. companies or Scandinavian companies. They have lands in different continents, they have mills in different continents, and they are marketing their products in a global marketplace. Carbon, wood, and biodiversity are all recognized as global issues now. People are actually selling carbon credits in one hemisphere to countries in another hemisphere. If that isn't enough evidence, consider this: about one-third of the graduate students in forestry at Oregon State University have come to school here from another country. The globalization of everything in forestry is just astounding.

Let's move on to forest management. Just about anywhere in the world, you'll find that forests are managed for many different purposes. Some are managed to produce resources that people need, while others are managed for recreational purposes; some are managed for national parks, wilderness areas, and so forth, and yet others as nature reserves. Sustainable forestry must be as broad as those many different purposes because it is those purposes that we wish to sustain. So, sustainable forestry involves diverse forest types, it treats each of them differently, and it focuses on trying to match the goals and capabilities and needs with the kind of management.

Now, what I'm saying to you here is that sustainable forestry is not defined by any single particular approach, and that it can be applied to the management and protection of a national park just as well as it can be applied to what you might call a tree farm or a fiber farm. Consider, three major points in this spectrum: industrial-strength forestry, integrated multi-benefit forestry, and wilderness or nature preservation forestry. I think of the most intensive types of forestry—almost on an agricultural mode of trying to put as much of the solar energy and the site's productive capability into the fiber—as industrial-strength forestry. Most of the world's industrial wood is going to come from these kinds of forest uses eventually. We are well on the way to a transition from extracting much of our wood from natural or semi-natural forests to getting most of it from this type of managed forest. There is a lot of potential for biotechnology and genetically modified organisms in industrial-strength forestry. Certainly if you increase productivity, equally important is to do that in ways that reduce environmental impact, such as by reducing the amount of chemicals, fertilizers, pesticides, maybe even water, used in production, while improving product quality and consistency. So as we consider the topics this week, it is appropriate to have a focus on the utility of industrial strength forestry. If predictions by some of the leading scientists are correct, we may end up with 10%–15%, perhaps even a little less, of the world's forested area in industrial-strength forestry. We probably will have a similar percentage in parks and wilderness areas, also vitally important for the values they sustain.

What that means is the remainder—the vast majority of the world's forests—will be in some intermediate kind of stewardship, management that is integrated for multiple benefits. These integrated multi-benefit forests also hold potentials for biotechnology. The goal here is to do a better job of optimizing joint production. A major role of integrated, multi-benefit forestry will be to protect vulnerable endangered species, including species that are vulnerable to exotic pests or diseases. If we can figure out how to put resistant genes into those native strains, we may be able to reduce the potential for the next white pine blister rust, or chestnut blight, those kinds of diseases where the native species and the host country of the disease organism have some kind of resistance.

The third major type of forestry, we might call it nature preservation or reserve forestry, is what you might think of being practiced in parks and wilderness areas—an extremely important part of the whole landscape mosaic of forests in providing all the things that we need. But it would be a mistake to think that these places are not managed. I know of only a few places in the world, and they're not in the United States, where these kinds of places are not managed. Here in the United States, we manage them very actively to reduce human activities and their impact, and to prevent exotic species from coming in or to try to get rid of them when they are there. We even have some national parks holding commercial timber sales to get the forest structure back to the conditions they want to sustain there. The key point is that these forests are not managed for economic gain. They are managed in ways that perpetuate their natural values. I think there will be some great potentials for genetically modified organisms here, especially if we can restore species that are endangered by exotic diseases and pests. And the great indirect benefit is that if we can figure out how to meet most of the world's wood needs from industrial-strength and integrated multi-benefit forests, it should allow us to put more of the forest land into this more protected classification.

Let us consider the roles of different owners for forest sustainability. Much of our focus in the past two decades has been on federal forestlands. That is the wrong place to put the focus for sustainable forestry. The most productive forests, and the largest land areas are held in private ownerships. These are not just industrial ownerships, they tend to be family ownerships—small tracts of land. There will be roles for national forests and national parks to play in sustainable forestry; they will largely be on the nature preservation, reserve forestry end of the spectrum. There will be roles for industry to play; they will largely be in the industrial-strength forestry end of the spectrum. But family forests, which make up about 60% of the forested area of the United States, are going to be major players. The percentages of how ownerships will contribute to the full spectrum of sustainable forestry will differ by countries of the world based on the kinds of tenured ownership they have. But just addressing the forest management parts of sustainability will not be sufficient. This is because of one fact: the managers and the forest industry that produces the wood products that we use, are not who create the demand. The demand for forest uses, products, and benefits—whether it's the water, or the recreation, or the wood or the biodiversity—comes from everyone who uses or wants those products.

So, the future for sustainability means that all people must be involved, including the forest managers, the manufacturers, and the end users. What we choose to use, how we choose to use it, where and how we decide to produce it and through what technologies, and what we decide to do with it when we are through—all of these are important points in reaching our goal of sustainability. We face a lot of challenges in aspiring to this goal in a world that is filling up with people. To date, we have been partially successful in using laws and regulations to prevent people from doing undesired things to forests and waterways. Now, we need some innovative policies that will entice people to do the right thing instead of just preventing them from doing the wrong thing. We need to recognize the trade-offs in the choices we make. In our world full of people, there are no easy choices. There are no choices without trade-offs in either the economic, or environmental, or social sectors. We need to continually invest in new knowledge and technologies, even if we just hope to keep up. We have to learn to protect water, and fish, and wildlife more effectively in our managed forests; to extend lifelong learning so all people engaged in forest conservation and the use of forests will understand what it takes to provide those uses; and to create a common ground on sustainability.

Now I'm going to take a little bit of a risk here and offer to you what I think is a simple five-step framework to organize our thinking and our dialog on sustainability. I don't mean to imply that any of this is going to be easy.

1. We must focus ecosystem transformations so that overall sustainability is enhanced. We cannot stop ecosystem transformations but we can make them more conducive to environmental health, economic vitality and community livability.
2. We must begin to focus on renewable natural resources, and use and conserve them wisely. Shift as quickly as we can, as much as we can, to solar-powered resources. This is certainly important for the United States, because we are such huge consumers of non-renewable resources.
3. We must develop knowledge, technology, and systems for sustaining desired social, environmental, and economic conditions, while approaching these desired conditions simultaneously. This is enormously difficult to do. We've tended to go after them one at a time. We have economic development schemes, and then we have regulations to stop the economic development schemes to protect the environment, and somehow in all of this, the communities get lost in the process. We have examples showing up on the front pages of our newspapers every day about what is happening to local people as these single-dimension agendas are being worked out.
4. We must manage ecosystems, and especially the human enterprises based on our knowledge and technologies to meet these combined social, environmental, and economic goals.
5. We need to pay attention to the fact that not everybody is benefitting at the same rate and to the same degree in the economic development of this world. It greatly saddens me that the gap between the really well off and the very poor keeps getting wider and wider. That just doesn't strike me as a sustainable proposition at all. It is inevitable that technology advances will occur that can help us meet human needs and goals for quality of life and equity. But if they don't occur in places like this, in academic settings, in open, public, democratic, rigorous scientific forums, then they are going to occur behind closed doors, in the dark of night, without the safeguards, without the public dialogue. It's not a question about whether genetically modified organisms are going to pop on the scene, and get into the environment. It's a question of who is going to set the ground rules for how that is done, and to what degree will we use this technology in managing nature and in equitably meeting human needs.

Those are the issues we must address this week. We also need to address concerns about transgenic trees themselves, issues about safety and security:

- Whether, and the degree to which, they will enhance productivity

- Whether, and to the degree to which, they are going to help us reduce the environmental impact of meeting people's needs for resources
- Whether we can use them to mitigate some of the undesired consequences of global change
- How to deal with intellectual property rights
- The ethics of intervening with creation or nature
- How are we going to make decisions on all this? Who gets to make the decisions? Who's going to be participating and who might be left out?

These are not the only issues we need to deal with in the area of sustainable forestry. There are many places where we can and will do better. We can have better harvest practices; we can improve our productivity practices; we can do better on maintaining biodiversity. But in many parts of the world, people are squabbling over forests, taking divisive polar "all-or-none" positions. So, one of our most important tasks is to create common ground (Figure 3). I see this as one of the biggest challenges that we face, in general, and specifically in the area of biotechnology. You, I am sure have encountered one or more of the extreme ideologies in your work. There are people who think that markets know best, and you just turn it over to the marketplace and everything will be fine. Or, that scientists know the answers, let's just ask the scientists and let them tell us what to do. Some people think that nature knows best, just leave nature alone and let it do its thing, and on and on. The point here is that when you take these kinds of fierce ideologies, and you take them to the extreme, they just rip apart the common ground. It leaves no room for people to come together and have a dialogue.

As I think through these though, it strikes me that you can take every one of these philosophical points and just turn its direction around (Figure 4). For example, if you know what you want to achieve, markets are a great way to get there. Everybody has some ideas; we have to have science to inform our choices so we know what the possibilities are as well as the consequences. The government does have a role; it's to set the standards. And locals know a lot, and we can probably reach better policies if we involve them in the deliberations. If we can take those ideologies and turn them into constructive views, we can probably rebuild the common ground that once existed, that we will certainly need to have to find prudent positions and choices on how to go forward on the concept of sustainability, and what role biotechnology and genetic engineering will play.

So it is time to talk about all the consequences of our choices. Will genetically engineered trees be part of our path to sustainability? That is the question for this symposium. If not, then how are we going to meet the needs of these billions and billions of people, and not just their material needs? If yes, then what will be the rules of engagement? The choices are up to us, and there are consequences to every choice we could possibly make.

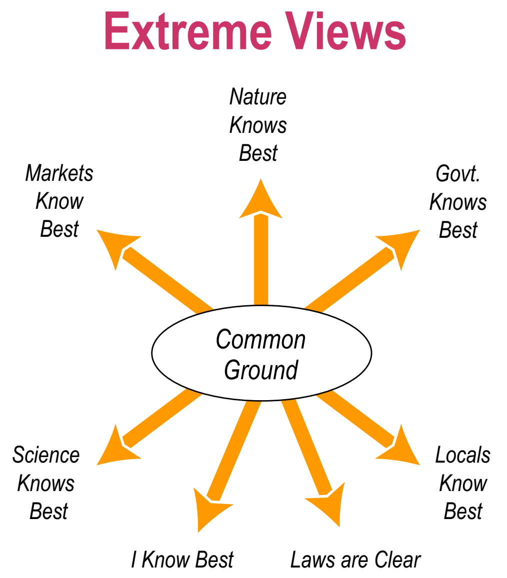

Figure 3. The challenge of creating common ground amid extreme ideologies is crucial for the future of biotechnology.

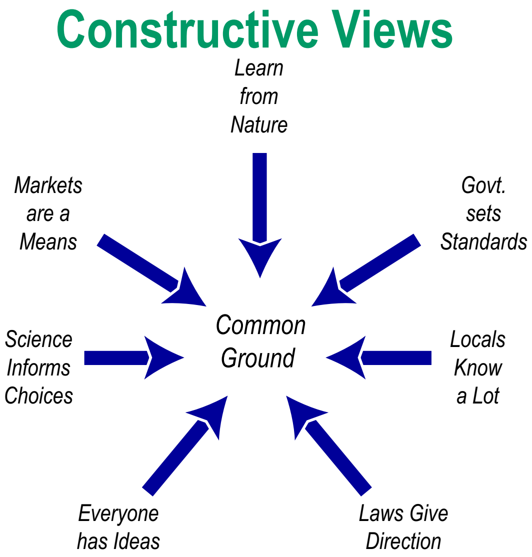

Figure 4. Ideologies can yield constructive views, which can in turn help rebuild common ground and inform choices that will guide us, not only in biotechnology and genetic engineering, but toward sustainability.

QUESTIONS FROM THE AUDIENCE

Toby Bradshaw, 'terrorist target'

> *Hal, I'd like to ask you, you mentioned in your talk that you don't see us returning to the forest that we had once upon a time. Could you elaborate on that? What do you mean? Do you mean that we'll never have any forests that are like they were once upon a time, or that we just don't have as much of that kind of forest as we once had?*

Well, I think the answer to that depends on how precisely you want to define the forests as they were once upon a time. We will never have the conditions of forests we had 'once upon a time', because we won't be returning to 'once upon a time'. Our climate is changing, our population is growing, our technology is different, we have put all sorts of stuff into the water and the air that never existed once upon a time. So, we're not going to go back and be able to overcome all of that and recreate a past that will never be again.

But does that mean we can't have diverse, productive, healthy forests, and lots of them? No, I think we can have that. We can even manage to perpetuate forests that are pretty close to the kind of natural diversity and function that they might have had if people weren't around. We won't be able to ever get there completely. It's just amazing to me—this morning there's an article in *The Oregonian* about the effects of air pollution coming out of Southern California on the national parks down there. We just simply aren't going to be able to overcome that. So the forests that we have in the future are going to be impacted by human enterprise. We can do the best we can to reduce that human enterprise, the effects of that enterprise as best we can, in the places that we want to maintain as naturally as is possible to maintain them. We can put our energy into producing some of the things we need in as small an area as we possibly can. I think you'll hear some good presentations on that this week. I'm not discouraged or pessimistic about future forests. The fact that we can't go back and make things like they were two or three hundred years ago doesn't trouble me.

Steve Strauss, Oregon State University

> *Hal, . . . I've heard comments from demonstrators that we've just messed with nature too much, and that biotechnology is obviously going to produce new kinds of genes that will enter the environment, genetic contamination, as it were. So let's just stop doing it. Let's just not mess with things anymore. What would you say to someone who has that point of view?*

Oh, boy. At what point do you want to start reversing the clock? Do you want to start with the things that we've done with humans, with crops? I don't know how to have a dialogue with somebody who wants to stop the world while they get off. The world keeps going forward. My biggest concern on genetically modified organisms is that if it's not done in places where we can have an open, scientific, democratic process of figuring out how to set the rules of engagement, then we are going to have to live with the consequences of somebody doing it somewhere else where they didn't have the benefit of that open democratic process. I would prefer that we didn't have to have the situation where we put this much intensive intrusion into nature, but I think the human population hasn't give us much option.

Hal Salwasser, final comments

You know, I want to make a comment here. I hope you all are taking a good lesson from Steve Strauss and Toby Bradshaw. They've got me giving a keynote talk and moderating a panel and then sharing perspectives at the end of the first two-day session. Now, I've got to figure that what they had in mind is that they want their Dean to understand what they are doing, and this is a way to absolutely guarantee that he keeps paying attention; it's really sneaky. I am a wildlife biologist by background, by the way, who focused on forest wildlife habitat. I don't know much, or I didn't know much about this area. I know a lot more now than I did a few weeks ago. I am really pleased that Steve and Toby have set me up for paying attention here, I expect to become relatively knowledgeable on this topic and understand what some of our faculty are up to. Good strategy!

Thank you very much for your attention, and I look forward to the next couple of days.

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Context and Goals for Ecosocial Symposium

Steve Strauss

It is my pleasure to begin this Symposium on Ecological and Societal Aspects of Transgenic Plantations, a part of the 10th international meeting of the International Union of Forestry Research Organizations, better known as IUFRO, Section on Molecular Biology of Forest Trees. The first IUFRO molecular biology meeting was organized by Howard Kriebel, a true pioneer on DNA studies of trees, in Ohio, USA, in 1985. Subsequent meetings of this group have been noteworthy for their high quality science and lovely venues, which have included Ontario, Canada; Lappland, Sweden; Lake Tahoe, California; Bordeaux, France; Scarborough, Maine, USA; Gent, Belgium, Quebec City, Canada; and Oxford, England.

It appears from the registration list that the trend of increasing attendance at these IUFRO meetings is continuing, and in fact may be accelerating. With more than 230 registered, representing 17 different countries, the attendance at this meeting substantially exceeds the number at the previous meeting (approximately 170). Despite the world controversy on plant biotechnology, and perhaps in part because of the world controversy, scientific interest in forest biotechnology continues to increase.

The large professional and media turnout at our meeting demonstrates that there is great scientific and social interest in forest biotechnology. From a scientist's view, particularly considering the obscurity of our field just a few years ago, this might seem surprising and inappropriate. However, on deeper reflection I think you will find it highly appropriate.

Human populations and resource consumption continue to grow, generating an increasing demand for wood and for the many other products and services of forests. Stresses on forests from humans, direct and indirect, also continue to mount. The world is searching for ways in which to both conserve and protect forests, while providing for a growing stream of forest products, with as little ecological disruption as possible.

It is no surprise that biotechnology, with its scientific depth and technological novelty, is viewed as holding considerable promise for sustainable resource production. But what kinds of biotechnologies do we want, and how should they be developed and agreed upon? These are difficult and complex questions, often with political, moral, and ethical dimensions beyond the reach of science.

Genomes, including those of trees, are being discovered and studied in detail for the first time in history. And methods for direct use of that knowledge, both via genetic engineering and DNA markers, have been developed that make it possible to act on this knowledge in the near term, and thus influence the genetic composition and management of forests. It should be no surprise that those with concerns about forest biotechnology are alarmed. Our field has deep and broad scientific power, and the potential to apply it. Many who do not understand the scientific issues fully, or do not trust the social institutions that regulate the science and technology, are apprehensive or even frightened. We need to accept this, and to honestly and openly provide reliable information and accurate research results in order to help society make its choices.

One important aspect of this meeting—technical considerations and conclusions aside—is that this very endeavor demonstrates a sincere attempt on the part of our scientific community to analyze, in an integrated, diverse, and open manner, the consequences of the technology we are developing. Toby and I strongly believe that it is the ethical responsibility of this community to do this, and we hope that the media, and even those opposed to biotechnology in forestry, even if they do not agree with our views, at least recognize the sincere effort we are making toward this end. This is not a community with its head stuck in the sand. It is a community that is reaching out and reflecting in the finest tradition of scientific reason and skepticism.

Toby and I chose the speakers because they possess diverse but thoughtful views. For many we know little more than this about their perspectives on forest biotechnology. I think you will see that this is not a highly pre-selected group chosen for a robotic love of forest biotechnology. It is a vigorous, wide-ranging debate that we seek.

This meeting focuses on biological science, with economics, business, and ethics as frameworks to help understand the motivation and context of the science and technology. We could have an entire meeting devoted to social and cultural issues of GM trees, however, that is not our current goal. In the spirit of good science, we therefore urge participants to avoid discussing GM trees as though they constituted a vague or generic set of concerns. The benefits and risks depend on the genes, how they are modified, the method of gene transfer, the intensity of research and safety evaluation, and the social as well as ecological context in which they might be deployed. There are myriad details to consider in biotechnology and they all matter. Thus, we ask that both speakers and the audience be as specific as possible, and whenever possible explain what benefits or risks you see for specific kinds of GM trees, and why.

Social views about resources, the roles of humans, ethical behaviors, and what constitutes sustainable development vary widely. The only certainty appears to be that the technological options that result from the rapidly growing science of biotechnology will neither be simple nor without controversy. As a biotechnology scientist, I find it hard to imagine a more exciting or challenging time to be living in.

INTRODUCTION TO PRESIDENT RISSER

To help set the stage for this conference, I would like to introduce Dr. Paul Risser, an internationally known ecologist and the President of Oregon State University. Dr. Risser was appointed the 13th president of OSU in 1996. He was awarded his PhD in 1967 from the University of Wisconsin, and has served in diverse faculty and administrative positions during his career.

Dr. Risser's professional interests include grassland and forest ecosystems, environmental planning and management, landscape ecology, and global change. He has led several multi-institutional and international scientific studies, and wrote and edited several books and over 90 invited chapters and scientific papers for refereed journals. He served as director of ecosystem studies at the U.S. National Science Foundation in 1975–1976, and is a fellow of the American Association for the Advancement of Science. He is a past president of the Ecological Society of America and the American Institute of Biological Sciences, and has consulted for the National Academy of Sciences, the Smithsonian Institution, the U.S. Environmental Protection Agency, and many other public and private organizations. In Oregon, he has been appointed by the governor to serve as chair of the Science Panel for Oregon's Environmental Stewardship Plan, and he chairs the Willamette River Restoration Initiative Board.

Dr. Risser's deep and broad background in ecology and biological sciences, including environmental policy issues, makes him uniquely well suited to launch this symposium on ecological and societal dimensions of transgenic forestry.

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Welcome to the First International Symposium on Ecological and Societal Aspects of Transgenic Plantations, in Conjunction with the IUFRO Conference on Tree Biotechnology in the New Millennium

Paul G. Risser
President, Oregon State University

For decades, breeding systems have been used to change, relatively slowly, the characteristics of plants and animals. Today we are rapidly learning much more about genes and genomes. Based on this new information, we now have the technology to more directly modify the properties of plants and animals.

This technological revolution is already underway, most strikingly in medicine, where an increasing number of pharmaceuticals are produced in genetically engineered organisms. Similarly, many different genetically modified crops have been produced or are in production, others are awaiting commercial acceptance, and still more are in the stage of advanced development. These manipulations have led to significant benefits in health care, food production, and environmental protection. They are not without controversy, however, as we all know.

From a strictly scientific viewpoint, the question is not whether these technologies are feasible, but rather, in what ways and under what conditions can they benefit humans and the environment? And at what point in the accumulation of this extraordinary new knowledge are we confident enough to go ahead with the technology, and to do so with a high probability of net social and environmental good?

Resolving these issues will never be easy because they confront the most fundamental of our beliefs and values. They intersect with human health, ecological integrity, privacy, assumption of risk, democratic process, and economic well being. And because there are concerns about threats to our very basic human values, people will disagree about these technologies, sometimes very strongly. Over the centuries, technologies have caused controversy, but this biotechnology is much more poignant because it seems more powerful and it affects the very essence of plants and animals.

This conference has been organized because the controversy has started to play itself out in forestry. Here it is complicated because in several ways, forestry itself can be controversial. We frequently use the words “forest” or “forestry” in imprecise ways. In some applications, we practice forestry with great intensity, where trees are clearly parts of wood farms—crops to be tended with one undisputed dominant product. In other places we manage forests with diverse ecological and social products in mind, of which wood may be only a modest output. In still other places, we harvest trees solely for the purpose of ecological management, if we harvest them at all.

Depending on the state of genetic knowledge and potential uses, biotechnology will fit in very different places along this management spectrum. At least for the immediate future, this genetic technology is likely to be confined to intensive plantation systems. These intensively managed systems occupy an extremely small portion of the world's forestry and agricultural landscape, yet they can produce enough wood to satisfy a disproportionate amount of the world's need. At least theoretically, high productivity from these plantations can relieve pressure for harvesting wild forests. In addition, with proper management, some of the new plant traits could have environmental as well as production benefits within plantation systems.

Consideration of the use of transgenic trees is focused on these plantation forests. Despite the relatively small area of these forests, concerns about the use of transgenic trees have been voiced from many quarters. Some raise concerns because they see a real threat to all wild forests; others fear a slippery technology slope from which there is no realistic return. Some of the strongest voices of concern are from genetic practitioners themselves—who, for more than a decade, have called for strict measures to mitigate ecological risks.

I am proud that an Oregon State University scientist, and the co-convener of this conference, Dr. Steve Strauss, has been at the forefront internationally in stimulating an open and vigorous debate. He and Toby Bradshaw have now put together this absolutely first-rate international symposium, the first of its kind in forestry. As speakers and participants, you will examine the social context and the ecological safety of genetically engineered forest species from virtually all major perspectives.

As I conclude these welcoming remarks, let me speak as a university president. Among the most significant values of great universities is the ability to bring together the best minds from many disciplines, and to focus these intellectual abilities on complex topics of particular importance to society. This intellectual pursuit must be accompanied by great attention to the ethical dimensions of the issue, and must encompass multiple perspectives supported by careful and thoughtful analyses. Moreover, these deliberations must be tested by peers and communicated to interested and affected constituencies.

Your challenge here will require rising to the standards and expectations of great universities. You must consider both the potential benefits and risks to our forests from this technology, you must do so in the context of a world that is growing hungrier for resources, and you must consider our shared responsibility for the health of our biosphere.

You will learn from each other, you will integrate ideas and information, and with a little luck, you will be able to forge a collective vision for moving forward on the most productive research agenda, and for constructing guidelines for the application of this technology. If it can be done, this carefully constructed conference, with the best experts from around the world, will certainly be successful.

Please accept my best wishes. Thank you.

Moderator Introductions

Steve Strauss

I would now like to introduce our competent moderators and then turn the symposium over to their care.

Last night you heard about the background of Dr. Hal Salwasser, Dean of the College of Forestry at Oregon State University and our keynote lecturer. Therefore, briefly, let me remind you that before coming to OSU, Dr. Salwasser was a Regional Forester and Research Station Director for the U.S. Forest Service, the Boone and Crockett Chair of Wildlife and Conservation at the University of Montana, and has been an active member of the Society of American Foresters, the Society for Conservation Biology, and the Wildlife Society. Dr. Salwasser brings a broad forest policy and ecological perspective to the symposium.

Dr. Clegg is a population geneticist who got his BS and PhD degrees from the University of California at Davis, working there under the eminent geneticist Dr. Robert Allard. He was a Professor at Brown University, the University of Georgia, and is presently a Distinguished Professor of Genetics at the University of California at Riverside—where he also served as Dean for six years. Dr. Clegg has published over 130 peer-reviewed publications, all at the cutting edge of population and molecular genetics. He is a past president of the American Genetic Association and the Society for Molecular Biology and Evolution, and was elected to the National Academy of Sciences in 1990—where he has participated on a number of committees and boards, including as chairman, from 1992 to 1995, of the National Research Council Committee on Scientific Issues in the Endangered Species Act. Dr. Clegg has also had editorial responsibilities for seven top journals in biology and population genetics. Dr. Clegg brings a strong plant evolutionary and molecular genetic perspective to the symposium.

POLICY AND ECONOMICS

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The Economic Contribution of Biotechnology and Forest Plantations in Global Wood Supply and Forest Conservation

Roger A. Sedjo

ABSTRACT

Over the past 30 years industrial plantation forests have become a major supplier of industrial wood. The reasons for this change are several and include the improved economics of planted forests due to technological innovations, the increases in natural forest wood costs due to increasing inaccessibility and rising wood costs from natural forests due to various pressures from environmentalists to reduce harvesting in old-growth forests.

Forestry today is on the threshold of the widespread introduction of biotechnology into its operational practices in the form of sophisticated tissue cultures, which produce clonal seedlings, and through the use of genetically modified organisms (GMOs), which produce desired tree and wood traits. As more of the world's industrial wood is being produced on planted forests, the potential to introduce genetic alterations into the germ plasm utilized in planting is obvious. In many cases the biotechnology likely to be introduced in forestry is simply an extension of that being utilized in agriculture, e.g., herbicide-tolerant genes. However, biotechnology in forestry is also developing applications unique to forestry, e.g., genes for fiber modification, lignin reduction and extraction, and to promote straight stems and reduced branching.

This paper discusses the growing role of plantation forests and the potential impacts of biotechnology on forestry. Traditional breeding and some aspects of biotechnology are discussed briefly and some of the various types of biotechnological innovations in progress in forestry and that may be forthcoming over the next decade or two are identified. A quantitative estimate is made of the potential economic impact of one transgenic application—that of the herbicide-resistant gene in forestry—and some of the potential environmental benefits associated with various types of biotechnology innovations are discussed. The potential benefits from the introduction of biotechnology to forestry promise to be large. For example, the widespread use of the herbicide-resistant gene for planted forest establishment is estimated to have potential cost-savings approaching $1 billion annually. The economic benefits will be found in the form of lower costs and increased long-term availability to consumers of wood and wood products.

Additionally, there is the potential for substantial environmental benefits from biotechnology in forestry. An environmental implication of the increased productivity of planted forests due to biotechnology is likely to be that large areas of natural forest might be free from pressures to produce industrial wood, thereby being better able to provide biodiversity habitat. The shift away from harvesting natural forests to alternative plantation wood sources is already well underway. Also, other environmental benefits from forest biotechnology are likely. Through biotechnology, trees can be modified so as to allow them to grow in previously unsuited areas, e.g., arid and saline areas. This characteristic could not only increase wood outputs, but might be appropriate for promoting increased carbon sequestration, which could contribute to the mitigation of the global warming problem, or through the provision of other environmental functions, such as enhanced watershed protection. Additionally, biotechnological innovation can be used in the resto-

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ration and rehabilitation of badly disturbed species or habitats. For example, biotechnology gives promise for the restoration of the almost extinct American chestnut tree in the United States. Finally, biotechnology gives promise of providing enhanced potential for carbon sequestration from more rapidly growing planted forests. This could result in a greater contribution of forest sinks to addressing the global warming problem.

The health, safety, environmental and ownership dimensions of biotechnology sometimes raise concerns, although in forestry, these differ in some important ways from the concerns of agriculture. Wood is rarely ingested directly by humans and thus, food health or safety is generally not an issue, although cellulose is sometimes used as a "filler" in food products. Also, ownership and property rights issues related to biotechnological innovations appear to be more tractable in the longer harvest rotation of forestry than in typical seasonal agriculture. In most cases the concerns associated with forestry related to the possibility of genetic escape from transgenic to wild trees. Although many of these risks appear to be negligible, transgenic trees that involve significant risks could be avoided while society still provides for the introduction of negligible risk plant genetic alterations.

Over the past 30 years industrial plantation forests have become a major supplier of industrial wood, gradually displacing wood from natural forests. The reasons for this change include the improved economics of planted forests due to technological innovations, relative increases in wood costs from natural forests due to rising extraction costs, and pressures by environmental activists to reduce harvesting in old-growth forests.

Forestry is currently undergoing an important transition from a wild resource, which had typically been foraged, to a planted agricultural crop, which is harvested periodically, as are other agricultural commodities—only the time scale for forestry is longer. The transition of forestry from foraging to an agricultural cropping mode has been underway on a significant scale only within the past half century or less (Sedjo 1999). Planted forests benefit from the same types of innovations that are common in other agriculture. As with other agriculture, economic incentives for investments in plant domestication, breeding and plant improvement activities will occur when the investor can capture the benefits of the improvements and innovations. As in other types of agriculture, early plant improvements involved identification of trees with desired traits and attempts to capture offspring that had the desired traits through the identification of superior trees. In recent decades traditional breeding techniques have been practiced in forestry as they have been in other agriculture. In the 1990s, however, modern biotechnology, including tissue culture, began to be undertaken in earnest in forestry. Additionally, a relatively large number (124) of confined traits of transgenic trees have been undertaken in the U.S., but only one transgenic tree species (papaya) has been authorized for release (McLean and Charest 2000).

The benefits from the introduction of biotechnology to forestry have the potential to be large. The economic benefits will be found in the form of lower costs and increased availability to consumers of wood and wood products. Additionally, biotechnological innovation has the potential to beneficially address a number of important environmental issues. Biotechnology can be used in the rehabilitation of habitats under pressure either from an exotic disease, as with the American chestnut tree (*Castenea dentate*) in the United States (Bailey 1997), or from invasive exotics. Additionally, an implication of the increased productivity of planted forests due to biotechnology may be that large areas of natural forest might be free from pressures to produce industrial wood, perhaps thereby being better able to provide biodiversity habitat. Also, through biotechnological improvements trees can be modified so as to allow them to grow in previously unsuited areas, e.g., arid lands, saline areas and so forth, thereby providing missing environmental functions, such as watershed protection. Such uses could not only increase wood outputs, but might be appropriate for promoting increased carbon sequestration in forest sinks and thereby contributing to the mitigation of the global warming problem (IPCC 2001).

The ownership and environmental dimensions of biotechnology in forestry differ in some ways from agriculture and so raise somewhat different questions. Ownership and property rights issues related to biotechnological innovations appear to be more tractable in the longer harvest rotation of forestry than in typical seasonal agriculture. This is because it usually takes several years before a tree will flower and the seed is available; by that time the seed technology may have become obsolete. On the environmental side, unlike most agriculture there are few major concerns for direct health or safety from the consumption of genetically modified wood products, although cellulose is sometimes used as filler in food products. There are, however, concerns related to genetic transfers that might occur between transgenic and wild trees, and the potential implications for the natural environment.

This paper is organized as follows. The general introduction of plantation forestry biotechnology is followed by a discussion of the application of tradition breeding and modern biotechnology to tree improvements. The next section presents a broad overview of the application of traditional breeding and modern biotechnology, including genetic modification, to trees. The section also discusses the various types of biotechnological innovations in forestry that could be forthcoming in the next decade or so. The third section undertakes a case study that estimates the potential benefits associated with the use of a herbicide resistant gene in forestry and discusses broadly the types of potential economic benefits that society could realize from biotechnology. This is followed by a discussion of potential environmental benefits and another section on concerns associated with biotechnology. Finally, the paper presents a summary of the implications of biotechnology to forestry.

OVERVIEW

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

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

Changes driven by technology, however, are not new. Hayami and Ruttan (1985) have pointed out that in the United States, most of the increased agricultural production that occurred in the two centuries before 1930 was the result of increases in the amount of land placed in agriculture, and most of the increased production reflected increased inputs in the form of labor saving technology—either animal or mechanical. In Japan, however, where land was limited, substantial improvements in rice productivity were made by careful selection of superior, yield-increasing seed. Land productivity in grain production in the United States showed little increase until the 1930s, as most of the gains in production were due to innovations that allowed more land to come into production, e.g., new equipment and mechanization. By contrast, land productivity in Japan was a function of biotechnological improvements in the form of improved seed and increased yields. However, in the United States after the 1930s, when most of the highly productive agricultural land was in the U.S., the focus of innovation was redirected to plant improvement, which increased land productivity through higher yields. Until fairly recently these improvements were achieved through the use of traditional plant breeding techniques, which gradually increased agricultural yields.

Plantation Forestry

Planted forests for timber began in earnest in the 19th century in Europe and about the middle of the 20th century in North America. Over the past 30 years industrial plantation forests have become a major supplier of industrial wood. The reasons for this change are several. These include the improved economics of planted forests vis a vis natural forests, due in large part to technological innovations that increased planted forest productivity as well as to the relative increases in wood costs from natural forests due to rising extraction costs and pressures by environmental activists to provide more stringent harvesting standards thereby reducing harvesting in old-growth forests.

In recent decades traditional breeding techniques have been practiced in forestry as they were in other agriculture. Early improvements in trees involved identification of “superior” trees with desired traits and attempts to capture offspring having the desired traits. The planting of genetically improved stock began about 1970. In the 1990s, modern biotechnology, including tissue culture and genetic modification, began to be undertaken in forestry in earnest. As more of the world’s industrial wood is being produced on planted forests, the potential to introduce genetic alterations into the germ plasma utilized in planting is obvious. Commercial forestry today is on the threshold of the widespread introduction of biotechnology in the form of sophisticated tissue cultures for cloning seedlings, and in the form of genetically modified organisms.

Early tree planting activities typically consisted of replanting seedlings after timber harvest. Factors important in the decision to replant included property rights—so that those who bore the costs of replanting would be able to capture the benefits of the future harvest—and protection capacity, which helped ensure that the tree crop would not be destroyed prematurely by pest or fire. It is not a coincidence that widespread tree planting occurred only after forest control had reduced substantially the incidence of forest wildfire (Sedjo 1991). Much of the early planting in the United States took place on lands that once had been naturally forested; but in more recent decades, it has occurred on land that had previously been used for agriculture. In the South, for example, such land had often been in cotton or tobacco. A similar phenomenon was seen in newly established planted forests overseas. In New Zealand, forests were planted on sheep pasture, in Chile, on marginal grain lands, in Argentina and Brazil, forest were often established on grasslands.

It was soon recognized that if the costs of planting were to be undertaken, the effect would be enhanced to the extent that improved seed or tree seedlings could be used. Thus, the decision to plant also provided incentive for tree improvement. Initially, tree improvement was accomplished through traditional breeding techniques.

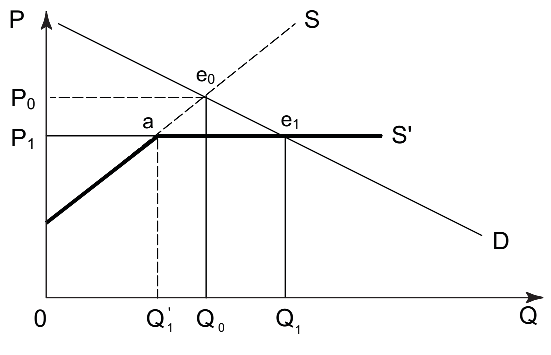

Figure 1. Industrial wood.

The Effects of Plantation Forests

Figure 1 provides a simple schematic that illustrates the effects associated with the lowering of costs provided by planted forests. In the absence of forest plantations the volume of industrial wood harvested in a period is determined by the intersection of supply, S. and demand, D, at eo. In this situation price is Po and the quantity harvested is Qo. The introduction of relatively low cost plantation forestry is represented by the line segment aS’. At price P1 plantations provide cheaper source of industrial wood than do natural forests. This new source of timber results in a new equilibrium, e1, with a lower price, P1 and a higher harvest volume, Q1. Notice, however, that the volume harvested from natural forests in reduced from Q0 to Q1'. This reflects that fact that the low-cost plantation wood is displacing wood from natural forests. The effects of biotechnology are to future reduce the costs of production thereby shifting down even further the aS' portion of the supply curve (not shown in Figure 1).

Impacts of Biotechnologically Induced Changes in Forestry

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

Table 1. Transitions in forest management and harvests.

Type	Period
Wild forests	10,000 BC - present
Managed forests	100 BC - present
Planted forests	1800 - present
Planted, intensively managed	1960 - present
Planted, superior trees, traditional breeding techniques	1970 - present
Planted, superior trees, genetic modification	2000 - future

Table 2. Global harvests by forest management condition, circa 1995.

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

Source: Sedjo 1999.

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

Forest management surely began in part of the world more than 2000 years ago. For example, written management directives appeared in China as early as 100 BC (Menzies 1985). However, significant areas of managed forest probably were not common in Europe until the Middle Ages. Planted forests began in earnest in the 19th century in Europe, but not until the middle of the 20th century in North America. The planting of genetically superior stock began about 1970, and the serious planting of genetically modified trees is just now beginning in parts of the subtropics, such as New Zealand and South America.

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

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

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

TRADITIONAL BREEDING

Selection

Tree improvement most often has relied on traditional breeding techniques like selection of superior (plus candidate) trees for volume and stem straightness, and grafting these into breeding orchards and producing seed orchards. When breeding orchards begin to flower, pollination of selections is artificially controlled, seeds are collected, progeny tests are established, and the best offspring are chosen for the next cycle of breeding. 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. This contributes to the more efficient production of industrial wood and to an improved quality of the wood output of the forest. In the past, operational quantities of seed from production seed orchards were derived from open pollination. Today, however, more sophisticated large-scale, controlled-pollination techniques are in place that offer the potential of further improvement of the offspring of two superior parents.

Table 3. Gains in loblolly pine from various traditional breeding approaches.

Technique	Increase in yields (%)
Orchard mix, open pollination, first generation	8
Family block, best mothers	11
Mass pollination (control for both male and female)	21

Source: Personal communication with researchers, Westvaco Corporation, Summerville, SC.

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

Hybridization

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. In the United States, for example, several hybrid poplars have shown remarkable growth rates, which exceed those found in parent populations.[1] The same is true for the *Eucalyptus grandis* and *urophylla* hybrids in many parts of the tropics and subtropics.

BIOTECHNOLOGY

Biotechnologies used in forestry fall into three main areas: the use of vegetative reproduction methods, the use of genetic markers, and the production of genetically modified organisms (GMOs) or transgenic trees. Most of the biotechnologies used in forestry today are in the category of tissue culture and molecular marker applications (Yanchuk 2001).

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[1] *Growth in hybrid poplar stands is 5-10 times the rate of native forest (Toby Bradshaw, University of Washington, personal communication).*

Cloning and Vegetative Reproduction

Vegetative reproduction comprises a broad range of techniques involving the manipulation of plant tissue that ultimately allows for vegetative reproduction of the whole plant. Tissue culture broadly refers to clonal techniques of growing plant tissue or parts in a nutrient medium containing minerals, sugars, vitamins, and plant hormones under sterile conditions. However, for some tree species, cloning approaches have been limited thus far (Pullman et al. 1998). In general, there has been greater success cloning hardwoods, e.g., poplar and some species of eucalyptus, than conifers.

The development of cloning techniques in forestry is important for a number of reasons. First, if superior trees are available, an approach must be developed to allow for the propagation of large numbers of seedlings with the desired characteristics if these traits are to be transferred into a planted forest. With tree planting often involving more than 500 seedlings per acre,[2] large-scale planting of improved stock would require some method of generating literally millions of genetically upgraded seedlings at a relatively low cost. The costs of the improved seedlings are important, since the benefits of improved genetics are delayed until the harvest. With harvests often occurring 20 years or more after planting, large costs for improved seed may seem difficult to justify financially. However, if the costs of plantings are going to be incurred, the incremental costs associated with planting improved genetic stock are likely to be quite modest, and therefore may be financially justified. Additionally, because the clone provides the vehicle through which desired foreign or artificial genes are transferred, cloning techniques must be developed in order for genetic engineering in forestry to be viable.

The ability to use inexpensive cloning techniques varies with species and genus. For some species, typically hardwoods, cloning can be as simple as using the vegetative propagation properties inherent in the species to accomplish the genetic replication. This might involve simply taking a portion of a small branch from a desired superior tree and putting it into the ground, where it will quickly take root (rooted cuttings). Where vegetative propagation is part of the natural process, large amounts of "clonal" material can be propagated via rooted cuttings, the cuttings of which come from "hedge beds." Here the process continues until sufficient volumes of vegetative materials with the desired genes are available to meet the planting requirements.

Eucalyptus, poplar, and acacia tend to be effective propagators. Other genera propagate less readily. Many species in the pine family, e.g., loblolly, and to a lesser extent, slash pine, are difficult propagators. Radiata pine, common in plantations in New Zealand and Chile, appears to have the best record on this account. Propagation improves when certain procedures are undertaken. For example, using the shoots emerging from newly trimmed clonal hedges increases the probability of successful regeneration. For many species, however, the process is more difficult, as simple vegetative propagation does not normally occur or occurs only infrequently. Here, "tissue culture" techniques provide the tools to quickly produce genetically engineered plants and clones to regenerate trees with desired traits (Westvaco 1996, pp. 8–9).

Genetic Markers

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

In recent years, molecular approaches to tree selection and breeding have shown significant promise. The molecular approach, although limited in application by its expense, involves genetic material being identified, collected, bred, and tested over a wide range of sites. Rather than simply

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[2] *It is estimated that 4 to 5 million trees are planted in the U.S. every day.*

choosing specific tree phenotypes on the basis of their outward appearance, the molecular approach identifies the areas of the chromosomes that are associated with the desired traits. "Markers" are used to identify the relative position of genes on the chromosome that control expression of a trait. This approach exploits the genetic variation, which is often abundant, found in natural populations. Molecular markers and screening techniques can be used to examine the DNA of thousands of individual trees to identify the few, perhaps less than a dozen, with the optimal mix of genes for the desired outputs. These techniques are currently being applied to the development of improved poplar in the United States and eucalyptus in Brazil.[3]

Recent work on hybrid poplar in the Pacific Northwest has shown a 20% increase in yields in plantations and an additional 20% on dry sites where irrigation can be applied (east of the Cascade Mountains).[4] Growth rates with these plantations are impressive. Yields are about 7 tons per acre, or about 50 cubic meters per hectare and improvements in the yield continue.[5] These growth rates are approximately three times the growth rates of typical pine plantations in the southern United States. Elsewhere in the world, for example, Aracruz in Brazil, yields of hybrid eucalyptus are reported to have more than doubled those of earlier plantings.

Genetically Modified Organisms (GMOs)

The term biotechnology is often associated with generic transformations as it involves 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—e.g., the promise of controlling the lignin in trees is dependent on the ability to identify and modify lignin genes, thereby altering the amount, type, and form of lignin that is produced in the tree (Hu et al. 1999). As noted, the ease of gene introduction (transformation) varies with different tree species and genus, and is generally more difficult in conifers than in hardwoods.

FUTURE BIOTECHNOLOGICAL INNOVATIONS IN FORESTRY

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

These attributes or traits can be characterized as silvicultural, adaptability, and wood quality (Table 4). Silvicultural traits would include growth rate, nutrient uptake, crown and stem form, plant reproduction (flowering), and herbicide tolerance. Growth potential, for example, has a substantial genetic component, with rates differing by 50% between families or different clonal lines. Traditional breeding approaches are steadily improving elite-line yield potentials. A subset of these traits is found in Table 5. These traits include those that are most likely to use biotechnology for further commercial development. The first three traits of the list in Table 5 are traits that, in the judgment of many experts, could be featured prominently in biotechnological innovations in forestry over the next decade.

Planted trees typically require herbicide and, in some cases, pesticide applications for one or two years after planting. The introduction of a herbicide-resistant gene can reduce the costs of herbicide applications by allowing fewer, but more effective applications without concern over damage to the seedlings. The use of a pest-resistant gene can eliminate the requirement to apply the pesticide altogether. Flowering control allows a delay of several years in

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[3] *Toby Bradshaw, Director of the Poplar Molecular Genetic Cooperative at the University of Washington, Seattle, personal communication. Also see Westvaco 1997.*

[4] *Toby Bradshaw, University of Washington, personal communication.*

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

Table 4. Forest traits that can be improved through biotechnology.

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

Source: Context Consulting provided information on potential innovations and their likely cost implication based on the best judgment of a panel of experts.

Table 5. Traits of interest in forestry.

- Herbicide tolerance
- Flowering control
- Fiber/lignin modification

- Insect tolerance
- Disease tolerance
- Wood density
- Growth
- Stem straightness
- Nutrient uptake
- Cold, wet, drought tolerance

flower initiation, non-flowering habit, or sterility. This control may be useful in preventing certain transgenic plants from transmitting genetically modified matter to other plants and/or from migrating into the wild.

As with pest resistance, disease resistance is also important, and the technology for genetic modification for disease resistance is fairly well developed. In New Zealand, for example, the first applications of genetically modified pine (*Pinus radiata*) are likely to involve “stacking”, that is, combining several genetically modified genes, perhaps including those of pest- and disease resistance and flowering control, in the seedling. Lignin control is viewed by the industry as an important priority. Trials with low lignin trees have already been undertaken in Aracruz Cellulose in Brazil (Claes Hall, personal communication, 20 January 2000).

BENEFITS OF BIOTECHNOLOGY

Benefits come in different forms. The economic benefits can be realized in the form of lower market costs for producing products. This typically converts into lower prices for consumers of those products. Some of these cost reductions are examined in detail later in this paper. Additionally, benefits can be realized through the development of increased quality and/or new products. These benefits are typically recognized within the market and are reflected by cost or price changes.

Benefits can also be realized outside the market. In agriculture, for example, benefits can accrue due to increased protein content in genetically modified rice. One important set of nonmarket benefits in forestry has been the substitution of plantation grown wood for the wood of primary forests. This has reduced the commercial logging pressure on natural forests, thereby reducing pressures on certain biodiversity and habitat (Sedjo and Botkin 1997). Modified tree species also show promise of being useful in providing environmental services in areas where trees now may have difficulty surviving—for example, in arid or drought-prone areas, areas with saline conditions or frost zones. Also, given the potential of biological sinks as a tool to mitigate the build-up of greenhouse gases associated with global warming, the ability to establish carbon sequestering plantations in regions not currently forested could become a very important tool in mitigating climate change (IPCC 2001).

Productivity

A distinguishing feature of the introduction of technology is increased productivity, e.g., in output per unit input. Alternatively stated, technology can be viewed as either cost reducing or yield (output) enhancing. From a societal point of view, this implies that society gets more output for its expenditure of inputs, i.e., a societal increase in efficiency. For the consumer, the implication typically is that relative prices of the desired good fall compared with what they would have been in the absence of the innovation. Plantation forestry has enjoyed success in recent decades, in part, because it has experienced cost-reducing technology thereby giving planted forests a competitive advantage over natural old-growth forests (Sedjo 1999). Furthermore, the opportunities with the application of biotechnology to forestry appear substantial.

Tree Improvements

With the planting of trees for industrial wood production, there is an inherent incentive to improve the quality of the germ plasma so as to generate tree improvements that can be captured at harvest. Tree improvements can take many forms (Table 6). Thus far, the most common emphases of tree improvement programs are increased growth rates, stem form, and disease resistance. Growth typically refers to wood volume growth or yields. Disease- and pest-resistance traits are also desired to promote or insure the growth of the tree. Resistance traits may be oriented to specific problems common in the growth of particular species or to extending the climatic range of certain species. For example, the development of frost-resistant eucalyptus would allow for a much broader planting range for this desired commercial genus. Other improvement possibilities include, as in agriculture, the introduction of a herbicide-resistant gene to allow for more efficient use of effective herbicides, especially in the establishment phases of the planted forest. Besides ensuring establishment, survival, and rapid growth of raw wood material, tree improvement programs can also focus on wood quality. Wood quality includes a variety of characteristics, including tree form, fiber quality, extent of lignin, improved lignin extractability, and so forth. Furthermore, the desired traits vary by end product. Wood quality may involve one set of fiber characteristics for pulping and paper production and another set of characteristics for milling and carpentry. Wood desired for furniture is different from that desired for framing lumber. In addition, some characteristics are valued not for their utility in the final product, but for their ease of incorporation into the production process.

Table 6. Tree improvement programs.

Important attributes

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

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

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

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

Anticipated Cost Saving Innovations

A recent study (Table 7) identified a number of innovations in forest biotechnology believed to be feasible within the next decade or two and estimated the possible financial benefits of their introduction.[6] The development costs of the innovations are not considered.[7] The innovations noted in Table 7 suggest a potential decrease in costs and/or an increase in wood volume or quality. Rates of return have been estimated from many of them. For example, the 20% increased volume due to the cloning of superior pine is estimated to provide a financial return of about 15%–20% on the incremental investment cost of $40 per acre. This assumes initial yields of 15 m^3 per ha per year and a stumpage price of $20 per m^3. Similarly, cost savings should be realized for improved innovations that reduce the amount of low value juvenile wood or reduce the amount or difficulty of extracting lignin in the pulping process.

In another example given in Table 7, the herbicide and weeding potential cost savings in a Brazilian planted forest due to the herbicide tolerance trait is estimated to generate an immediate reduction of $350 per ha in the establishment costs in the two- to three-year establishment period. Obviously, this potential degree of financial benefit, which reduces initial establishment costs on the order of 40%, is substantial. Biotechnological innovations that modify wood fiber characteristics so as to reduce pulping costs have also be estimated. The value added from pulping is about $60 per m^3 or $275 per ton of pulp output. If these costs are reduced $10 per m^3, this provides a surplus (or effective cost reduction) of about $47 per ton of wood pulp (assuming 4.7 cubic meters per tonne of pulp), assuming wood prices are not affected. This type of innovation would be important to the forest sector, since a mill would be willing to offer a premium for wood fiber that had a low processing cost. If the improved fiber is common, then it would be expected to create processing cost savings that would eventually be passed on to the consumer. Thus, substantial cost savings could be generated.

Table 7. Possible financial gains from future biotech innovations.

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

* The actual cost savings experienced by the tree planter will depend importantly on the pricing strategy used by the gene developer and the portion of the savings to be captured by the developer and that passed on to the grower.

Source: Context Consulting.

A CRUDE ESTIMATE OF THE GLOBAL IMPACT: A CASE STUDY OF HERBICIDE RESISTANCE

This section examines the potential costs savings of a specific biotechnological innovation—the introduction of a herbicide-resistant gene—on the costs of establishing future commercial forests and thus on the potential future timber supply. By inference, the likely effect on harvests from natural forests is also examined. The approach used is that of a crude partial equilibrium approach,[8] which estimates the cost savings associated with the development of a specific innovation as applied to forestry—the herbicide-resistant gene. The

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[6] *The distribution of the benefits of a patented innovation is complex. Initially, one would expect most of the benefits of the innovation to be captured by the price charged for the improved product. Subsequently, however, the price charged for the new technology typically declines. At the end of the patent period, the technology becomes part of the public domain.*

[7] *As is well known, once the investment is made in innovation, it is a fixed cost and unrelated to the marginal cost associated with the distribution of the product.*

savings in plantation establishment costs are estimated on the basis of the data presented above. These savings are translated into the lowering of the supply curve for planting activity. This results in an incremental addition to plantings. Due to the delay between planting and harvest, the direct impact on harvests is delayed to the future timber supply.[9]

Figure 2 provides a schematic of the demand and supply for plantation forests. As the diagram shows, if the costs of plantation establishment decrease from Cost0 to Cost1, this is reflected in a downward shift of the supply curve from S to S'. other things constant, and the quantity of plantations increases from Q0 to Q1. The economic benefits are the cost savings, which is represented by the area between the two cost curves and bounded by the demand curve on the right and the vertical axes on the left.

Table 8 presents estimates of the cost reduction in plantation establishment for the herbicide-resistant gene used in this study. Forest plantation establishment involves incurring substantial costs in an early period in order to generate larger, but discounted, benefits at some future time. High-yield plantation forestry involves plantations with harvest rotations of from 6 to 30 years. To the extent that costs of establishment can be reduced, net benefits can be achieved. Experts estimate that herbicide resistance would reduce the costs of plantation establishment by an average of about $35/acre for fast-growing softwoods (reduced costs of 15%) and an average of $160/acre for fast-growing hardwoods (reduced costs of 30%) through the elimination of the costs of other pest mitigation activities.[10] In North America about 4 million acres are planted annually. If 98% (3.9 million) are softwood and 2.0% (0.1 million) hardwood, the potential cost reduction potential at current rates of planting would be $136.5 million for softwoods and $16 million for hardwoods or a total savings of $152.5 million annually.

Worldwide about 10 million acres of plantation forest are planted per year. If the plantings are roughly 50–50 conifer and hardwood and the plantings remain unchanged, the potential saving from the introduction of the herbicide resistant gene is $175 million for softwoods and $800 million for hardwoods, where the development of the clonal prerequisite is largely developed (Table 9). Thus the potential global cost savings is about $800 million annually, with enabling technology that is essentially available today for hardwoods, and roughly $975 million annually, once low-cost conifer cloning has been perfected. Thus, the near-term potential benefits are quite large, even if softwoods are not considered.

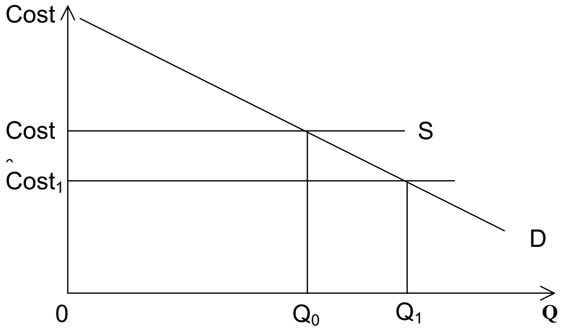

Figure 2. New plantation starts.

Another issue is the extent to which lower establishment costs would increase total plantation establishment. Of the 10 million ha of forest planted annually, we assume that about 1 million ha represents new industrial plantations.[11] Assume that the actual costs to the industry were reduced by the full amount of the cost reduction realized through the innovation, for example, that the innovation was priced at marginal cost. This would be an average reduction of 22.5% in plantation establishment costs. Under these circumstances what increase would be expected in the annual rate of plantation establishment? The expected amount would depend, in part, on the responsiveness of demand to price changes. This responsiveness is captured in the economist's use of price elasticities.[12] To examine this question, we de-

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[8] *A more sophisticated modeling approach would involve integrating estimates into a forest sector systems model (e.g. see Sohngen et al. 1999).*

[9] *It should be noted, however, that the anticipation of greater future supplies will effect current actions, including current harvests (see Sohngen et al. 1999).*

[10] *The percentages are based on an updating of plantation establishments costs as found in Sedjo (1983).*

[11] *Sedjo (1999) estimated this to be about 600,000 ha for the tropics and subtropics, while the model of Sohngen et al. (1999) estimated new plantations to be about 850,000 ha annually. The somewhat higher figure used in this study reflects the inclusion of new plantation establishment in the temperate regions and anecdotal evidence suggesting that these earlier estimates were on the modest side.*

[12] *Price elasticity is simply the percentage change in quantity divided by the percentage change in price.*

velop and estimate the impacts from three scenarios: the maximum impact, an intermediate impact, and a low impact (Table 10).

Scenario A: Maximum Impact—Given an initial total annual rate of global planting of 1.0 million ha and assuming an infinite supply elasticity and a unitary demand elasticity for forest plantation plantings (a derived demand), the estimated impact would be the establishment of an additional total planting area of 225,000 ha per year. This assumes that the additional planting would reflect current mix of planting. i.e., the additional planting would be divided evenly between conifer and hardwood. Furthermore, if we assume that growth rates on plantation forests would average 20 m^3 per ha per year for softwoods and 30 m^3 per ha per year for hardwoods, the result of the additional plantings would result in a future addition to total annual production at harvest of 2.5 million m^3/yr. If these increases in plantings were realized each year for a 20-year period, about 100 million m^3/yr of additional industrial wood production would be generated annually after 20 years.[13]

Scenario B: Intermediate Impact—Suppose the same conditions obtained as in Scenario A, except that the supply elasticity was 1.0. In this case a total of 112,500 additional ha planted per year would result in a total increased production at future harvest of 2.5 million m^3/year. After 20 years of planting this would generate about 50 million m^3/yr of additional continuous production.

Scenario C: Estimated Minimum Impact—The assumption is that supply elasticity remains a +1.0, as in Scenario B, but that the demand elasticity is –0.7.[14] In this case we estimate a total of 78,750 additional ha planted per year with an increase in total production at harvest of 1.969 million m^3 per year. After 20 years of planting at this rate the additional continuous wood production would be about 39.375 million m^3 per year.

Table 8. Herbicide resistance benefits.

- $35/acre ($87/ha) cost reduction for fast-growing softwoods*
- $160/acre ($400/ha) cost reduction for fast-growing hardwoods

*It should be noted that for many conifers low-cost clonal forestry is not well developed. Thus, the wide-spread application of GMOs to conifers is not feasible at this time. However, New Zealand appears to have a workable system for *Pinus radiata.*

Source: Context Consulting.

Table 9. Potential cost saving from herbicide resistant gene (in millions of U.S. dollars).

	North America	Total global
Hardwood	136.5	800.0
Conifer*	16.0	175.0
Total	152.5	975.0

* Assumes successful development of enabling commercial clonal technology.

Table 10. Scenario summaries.

Scenario	Additional plantings	1-year additional m^3	20-year additional m^3
Scenario A	225,000	5.00 million	100.0 million
Scenario B	112,500	2.50 million	50.0 million
Scenario C	78,750	1.97 million	39.4 million

BENEFITS OF FOREST BIOTECHNOLOGY: A SUMMARY

Economic Benefits

As noted, a distinguishing feature of the introduction of technology is increased productivity, for example, in output per unit input. From a societal point of view, this implies that society gets more output for its expenditure of inputs; there is a societal increase in efficiency. The above analysis suggests that the annual economic benefits in reduced costs associated with the introduction of only one transgenic gene, the herbicide-resistant gene, could reduce the global costs of the establishment of planted forests by as much as one billion dollars annually. This cost reduction implies an increased rate of tree plantation establishment into the indefinite future and more industrial wood at lower prices in the future. Of course, substantial additional economic benefits could be derived from the host of other biotechnological innovations,

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

[14] *This is approximately the recent FAO estimate of -0.67 for the elasticity of demand for industrial roundwood.*

including a variety of additional transgenic trees with various other economic advantages.

Furthermore, the increased biological and economic productivity of planted forests has important positive spillovers to the environment. Increased planted-forest productivity implies the creation of more low-cost plantation forests and lower-cost industrial wood associated with those plantations. Wood from planted forests develops a greater comparative cost advantage over wood harvested from natural forests. Thus, while harvests from planted forests increase, production from natural forests declines. In short, plantation wood is substituted for natural forest wood, thereby leaving the natural forests for other uses, including ecosystem and biodiversity preservation.[15]

Environmental Benefits of Forest Biotechnology

The above discussion has focused on the economic or financial benefits of biotechnology to forestry. These financial benefits are manifest through reduced costs and/or higher production of wood, and through enhanced quality through improved traits and wood characteristics, suitable for both solid wood products and pulp and paper products. Additionally, as discussed below and summarized in Table 11, biotechnology in forestry can be used to achieve a number of environmental outputs and generate improvement in various environmental objectives. In addition to the protection from harvests afforded natural and old-growth forests by the substitution of low-cost wood from plantations, biotechnology improved trees could be modified to specifically provide certain desired environmental services. Modifications that would allow trees to grow in previously unsuitable areas, such as arid and degraded lands, could enable trees to provide restoration benefits, as well as traditional ecosystem services such as erosion control and watershed protection. Additionally, certain desirable species could be modified to allow them to grow in areas that were previously unsuitable because of frosts or a cold climate. This modification could not only increase wood outputs, but might be appropriate for environmental objectives.

Additionally, biotechnology provides the potential of restoring species severely damaged through pests and disease, such as the American chestnut.[16]

And finally, forestry has been shown to have substantial potential for mitigating the build-up of atmospheric green house gases, including carbon, believed to be the cause of anticipated global warming (IPCC 2001). Biotechnology applied to forestry could assist in enhancing the carbon sequestration ability of forests, and thereby provide additional carbon mitigation possibilities.

To summarize, the benefits of biotechnology in forestry can be viewed as coming in two groupings. First, biotechnology has generated a number of innovations that will significantly reduce costs and/or enhance the quality of the forestry outputs, thereby enhancing society's efficiency in resource use. Some portion of these benefits is likely to be transferred to the consumer through lower prices,

Table 11. Environmental benefits.

Environmental outputs	Biotechnological innovations
Reduced pressure to log natural and old-growth forests.	Plantation wood from more productive forests will substitute for wood from natural forests at lower costs.
Protection forests can be established on degraded or arid lands.	Genetically improved trees with land protection and land restoration capabilities suited to poor sites.
Carbon sequestrating forest can be established on sites previously not suitable to forestry.	Genetically improved trees capable of substantial carbon sequestration suited to biologically poor sites.
Species restoration.	The potential species restoration of the chestnut.

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[15] *The argument that plantation wood substitutes for wood from natural forests is substantially different from the issue of land involved in grain production in that forestry compares a foraging with a cropping activity. A recent FAO study (1996) estimated the global demand elasticity of industrial wood at –0.67.*

[16] *The American Chestnut was decimated around the turn of the 20th century by a introduced fungus. However, the fungus acted only on the above ground portions of the tree. Thus, live roots remain and could provide the bases for a restoration should the fungus be controlled, through genetic modification. Appropriate genes appear to be available in the Chinese Chestnut.*

and we would expect the transfer to increase over time. Additionally, biotechnology has the potential to generate a number of environmental benefits through its effect on the competitive structure of the forest industry. In general, this will be through decreasing the competitive advantage of the harvest and use of natural and old-growth timber and increasing the substitution and use of plantation wood—thereby imparting a degree of protection from commercial logging to the natural and old-growth forests, which are viewed as having greater environmental value. Finally, the biotechnological modification of a tree can allow it to perform a broader and more useful set of both economic and environmental functions and services. These include, for example, enhanced carbon sequestration generally, and its potential in regions that have been degraded and are currently difficult for forestry. Biotechnology can also enhance other desired environmental objectives, such as restoration, watershed enhancement, and erosion control in areas typically not suitable to forests and/or areas subject to cold, frost, and drought.

POTENTIAL COSTS OF BIOTECHNOLOGY IN FORESTRY: SOME CONCERNS

Transgenic biotechnology has become quite controversial when applied to agriculture (e.g., see *Science* 1998). However, in drugs, medicines, and pharmaceutical applications, transgenic biotechnology is essentially without controversy. The nature of the controversy in agriculture has developed around at least five issues.

First, is the issue of ownership of the modified genes and the question of how much ownership/control the biotechnology companies have over their transgenic products after they have been distributed. An important element in the discussion relates to the ongoing controversy regarding the broader philosophical issue of the ownership of biodiversity and improved products. Are wild genetic resources the property of all of humanity or of the country in which they reside? And are developed biotechnology products the property of the developer or should they be available without royalty payment to all of humanity? (For example, see, Kloppenburg, Jr. 1988; Sedjo 1992.) This controversy continues to be manifest in the difficulties in interpreting and finalizing the "biodiversity treaty" coming out of the UNCED "Earth Summit" meeting in Rio de Janeiro in 1992.

The second issue in the overall controversy relates to the health, safety and environmental aspects of transgenic products. Although there is little or no evidence that transgenic foods are unsafe, health concerns are raised due to the lack of long-term exposure and experience with such products. The health issue is not generally raised for trees as they are not usually viewed as a human or animal food source.

A third issue with transgenic plants is the question of genetic transfer to nearby domestic or wild populations. For forestry the concern is largely with genetic transfer to wild populations. In many cases plantation tree species would be exotic and thus exchange would not be a factor. In cases where genetic exchange could be a problem, a method to prevent or reduce their "escape" would be to promote sterility or reduce or delay flowering (see DiFazio et al. 1999). The implications of gene escape are likely to differ depending on whether the gene would confer a selection advantage to the wild plants. This is likely to depend upon the nature of the genetic alteration.

A fourth issue relates to the impact of the biotechnology on the resistance of the targeted pest population. It is well known that pests adapt through natural selection to the introduction of pest-controlling chemicals. The same response would be expected to attempts at genetic pest control. As in agriculture (Laxminarayan and Brown 2000), in forestry there could be a problem of the pest population adapting to the modified gene and thereby undermining its longer-term effectiveness. The long period of forest growth would seem to exacerbate the problem, as it would allow insect populations many generations to develop a resistance mechanism. Various approaches are being considered to overcome this problem including the continuing development of new pesticides in agriculture and the use of refugia to dilute the development of resistance in the pest population.

Finally, there is the issue of whether biotechnology applied to agriculture will increase the demand for land, thereby putting increased pressure on natural habitats. Some recent work suggests this is likely to be the case if the demand for agricultural products is elastic (e.g., Angelsen and Kaimowitz 1998).[17] However, this is unlikely to be a problem in forestry where demand is almost always estimated to be inelastic and productivity of planted forests considerably greater than that of natural forests.

In some ways the biotech issues in forestry appear to be modest compared with those in food. Since wood products are not ingested they are unlikely to have any direct human health or safety effects, either in the short- or long run. The ownership issue associated with the use of seeds from transgenic plants to create subsequent crops is likely to be less important as well, due to the long periods required for flowering in trees.

A more pressing concern, however, relates to the potential for genetic transfer from the transgenic tree to the surrounding natural environment.[18] As noted, this is not a problem in cases where the tree is an exotic and therefore no similar species of trees are found in the natural environment, e.g., since conifer species are not indigenous to South America, the accidental transfer of genes from exotic conifer to indigenous conifer trees is precluded. Where the species is indigenous, an approach may be the introduction of sterility as a vehicle for preventing the release of genes that might transfer to the natural environment. Note that the major reason for introducing a sterility gene into trees is not, as in agriculture, to retain control over future seed sources, but rather to prevent the escape of genes into the natural environment through the tree-flowering process.

Finally, if modified genes do escape, how serious are the “expected” consequences or the “worst case” consequences? In the case of the herbicide-tolerant gene, the consequences of release into the wild are probably small. Herbicides are unlikely to be applied to most of the natural environment. If herbicides are to be applied, types can be used to which the escaped genes do not confer tolerance. In the intermediate and longer term, the herbicide in question will almost surely be replaced periodically in the normal course of product change and development. Thus, the presence of that modified gene in the natural environment appears unlikely to constitute any serious short- or long-term environmental problem. Similarly for genes that affect tree form or fiber characteristics, the release of this gene into the natural environment is unlikely to provide a competitive advantage in survival and therefore unlikely to have significant or adverse consequences.

However, this situation could change if a survival gene is involved. For example, the release of a Bt gene into the wild could constitute a more serious problem if it results in the altering of the comparative competitive position in dealing with the pests of various types similar natural vegetation. Ultimately, the seriousness of this problem depends importantly on the probability of the transfer of a survival gene into the wild, on the scale of the transfer, and on the comparative change in the competitive balance within the natural habitat. This becomes an argument for the introduction of controlled exotics.

SOME IMPLICATIONS OF BIOTECHNOLOGY FOR FORESTRY: WEIGHTING BENEFITS AND COSTS

The benefits of applying biotechnology to forestry are potentially huge. The estimates above suggests that the introduction of only one type of biotechnological innovation, a herbicide-resistant gene, could generate benefits estimated at up to $1 billion annually in reduced forest plantation establishment costs and an expansion in the rate of plantation establishment by up to 225,000 additional ha per year. The increased production would not only generate increased social welfare through lower commodity prices, but would also generate environmental benefits in the form of decreased harvesting pressure on natural forests.

Furthermore, it is well documented that there has been a gradual worldwide shift in industrial wood production from natural forests to plan-

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[17] *It has been noted that since cattle are increasingly being placed in feedlots where they consume grains, the total demand for grain, human and animal, may be elastic. This implies that if grain prices fall, e.g., due to biotechnology, the total area of land in grains could increase. However, it should be noted that where both grain and cattle are part of society's diet, the feeding of grain to cattle has resulted in a decline in pasture area. Thus, total agricultural land, grain plus pasture, may have decreased even if the area in grains increased.*

[18] *See Mullin and Bertrand (1998) for a detailed discussion of many of these issues in a Canadian context.*

tations. Such a trend could have advantageous effects on native forests and biodiversity in that as harvest pressures are relieved and native forests can be devoted to other purposes, including conservation. The more productive are forest plantations, the more they can deflect harvesting pressures away from natural forests.

Additionally, biotechnology applied to trees offers an additional tool in dealing with specific environmental problems, including land and water protection, as well as presenting the potential to deal more effectively with global warming and atmospheric carbon mitigation.

The costs of biotechnology in forestry are much more problematic. In many cases the potential costs of the introduction of biotechnology in forestry appear to be negligible or modest at best. Herbicide resistance and form and fiber modification appear to offer minimal potential damages. The greatest concern is probably related to the escape of modified genes into the natural environment. The costs associated with this are unclear, but in many cases would be negligible. Furthermore, most could probably be reduced substantially by the delay or elimination of flowering and/or by introducing the species into foreign environments where similar species are not found in the wild and gene transfer is highly improbable.

Finally, biotechnology in forestry takes many forms. Even if certain transgenic trees are viewed as potentially risky, there are a host of genetic modifications that offer negligible social risk.

SUMMARY AND CONCLUSIONS

The benefits of biotechnology in forestry, both economic and ecological, are potentially enormous. The widespread use of a herbicide-resistant gene in forestry could result in a savings of up to $1 billion annually. However, the benefits must be compared with the costs. Recently, biotechnology in agriculture has come under attack for its potential health, safety, and environmental risks. The application of biotechnology to forestry, however, poses somewhat different considerations than biotechnology's applications elsewhere. For example, direct health and safety risks appear nonexistent or negligible. The environmental risks that exist appear to relate largely to the potential for altered genes to move out of transgenic trees into the natural environment. The damages associated with the escape of many types of these activities are negligible and probably can be reduced substantially by the delay or elimination of flowering and/or by introducing the species into foreign environments where similar species are not found in the wild and gene transfer is highly improbable. Where the risks cannot be adequately mitigated, certain selected types of biotechnological activities could be precluded.

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*Restoring the Forests**

David G. Victor
Jesse H. Ausubel

ABSTRACT

The 20th century witnessed the start of a "Great Restoration" of the world's forests. Efficient farmers and foresters are learning to spare forestland by growing more food and fiber in ever-smaller areas. Meanwhile, increased use of metals, plastics, and electricity has eased the need for timber. And recycling has cut the amount of virgin wood pulped into paper. Although the size and wealth of the human population has shot up, the area of farm and forestland that must be dedicated to feed, heat, and house this population is shrinking. Slowly, trees can return to the liberated land. We develop a plausible and attractive scenario for how far this "great restoration" can proceed by 2050—if farmers lift yields at about 2% per year and thus grow ever more food on smaller areas of land, and if foresters continue the shift to high yield plantation forests, which reduces the wooded area that must be devoted to timber supply. The average timber yield needed to achieve our "great restoration" scenario is about 5 cubic meters per hectare per year. That can be attained without genetically modified (GM) trees, but insofar as GM trees allow for even higher yields, they make it feasible to shrink even further the area of production forests. Hectares freed from timbering can be available for other purposes such as protection of biological diversity, watershed protection and nature's intrinsic beauty.

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http://greatrestoration.rockefeller.edu.

SKINHEAD EARTH?

Eight thousand years ago, when humans played only bit parts in the world ecosystem, trees covered two-fifths of the land. Since then, humans have grown in number while thinning and shaving the forests to cook, keep warm, grow crops, plank ships, frame houses, and make paper. Fires, saws, and axes have cleared about half of the original forestland, and some analysts warn that within decades, the remaining natural forests will disappear altogether.

But forests matter. A good deal of the planet's biological diversity lives in forests (mostly in the tropics), and this diversity diminishes as trees fall. Healthy forests protect watersheds and generate clean drinking water; they remove carbon dioxide (a greenhouse gas that traps heat in the atmosphere) from the air and thus help maintain the climate. Forests count—not just for their ecological and industrial services but also for the sake of order and beauty.

Fortunately, the 20 century witnessed the start of a "Great Restoration" of the world's forests. Efficient farmers and foresters are learning to spare forestland by growing more food and fiber in ever-smaller areas. Meanwhile, increased use of metals, plastics, and electricity has eased the need for timber. And recycling has cut the amount of virgin wood pulped into paper. Although the size and wealth of the human population has shot up, the area of farm and forestland

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that must be dedicated to feed, heat, and house this population is shrinking. Slowly, trees can return to the liberated land.

In the United States, this Great Restoration began with a big stick. Horrified that farmers and loggers were stripping America of its trees five times faster than they were growing, and worried about the economic consequences of a “timber famine,” President Theodore Roosevelt created the federal Forest Service and pushed landowners to start sustaining timber resources. Since about 1950, U.S. forest cover has increased—despite the country’s emergence as the world’s bread and wood basket. Geographers have observed a transition from deforestation to reforestation in countries as distant as France and New Zealand, where new production methods have spared forests and regulation has locked the gains in place. Studies by forest experts in Finland reveal that by the 1980s, wooded areas were increasing in all major temperate and boreal forests. These mid- and high-latitude forests account for half the world’s total and span some 60 countries. Such forests today are also healthier: the biomass (or total amount of living matter) per hectare (100 meters square, or about 2.5 acres) has increased even more rapidly than the size of the forests themselves.

But the Great Restoration is far from complete. Despite major gains in some areas, the world’s sylvan balance sheet still bleeds trees, owing to widespread deforestation in the tropics. Yet even there, progress has begun to peek through. Preliminary satellite data suggest that the rate of tropical deforestation has slowed 10% in the last decade. New studies in tropical western Africa reveal that deforestation in that region is only one-third the rate previously believed, and in some areas forests are rebounding. Brazil, for its part, is often in the forest press. Farmers’ fires, cattle ranching, and timber cutting denude the Brazilian Amazon by perhaps half a percent each year, and the government seems powerless to stop it. By some estimates, four-fifths of Brazil’s local wood consumption is illegally felled. Yet at the same time, Brazil has become a powerhouse in forest planting. Established on already degraded and abandoned land, eucalyptus and pine stands in Brazil supply a rising fraction of the world’s lumber and paper and relieve the pressure on natural forests.

Yet still the world’s forest estate dwindles. Even in countries where woody areas are expanding, threats to the remaining uninterrupted original tracts of trees—what the World Resources Institute calls “frontier forests”—have not vanished. Earth’s trees therefore need a comprehensive and durable solution: to expand and accelerate the Great Restoration worldwide. Agriculture and logging—the two main threats to natural forests—must continue their transformation into modern, ultra-efficient industries.

The seedlings and saplings of this transformation have already been planted. But the progress and potential of modern agriculture and forestry remain little known to many policymakers, and requisite techniques are reviled by others who prefer “natural,” low-intensity production. And in much of the world, the conditions necessary for these new methods, such as affordable commercial energy and effective land-use regulation, remain elusive.

The chart illustrates the immense areas at stake. Two paths now stand open. Along one, leading to the “Skinhead Earth” scenario, quaint and

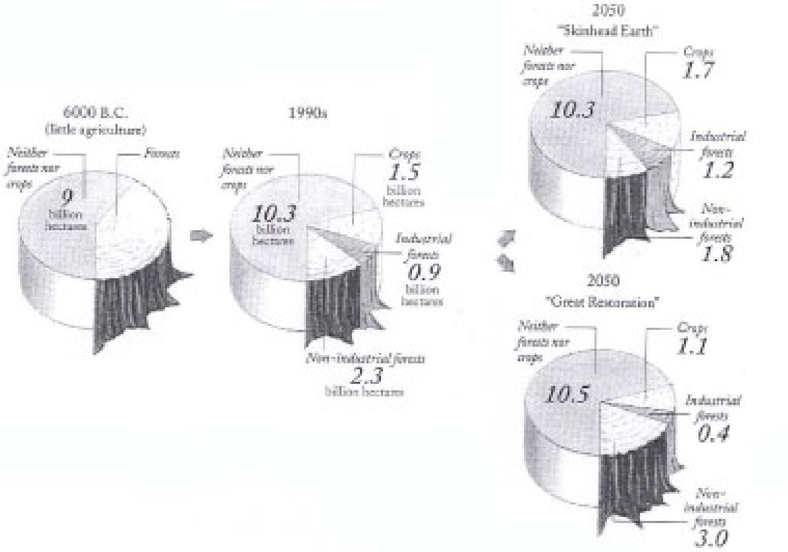

Figure 1. Sources (rounded estimates): 6000 B.C., World Conservation Monitoring Centre, World Resources Institute, and World Commission on Forests and Sustainable Development; 1990s, U.N. Food and Agriculture Organization Global Fibre Supply Model data; 2050, authors’ projections.

inefficient agriculture and forestry will persevere. By 2050, forests will dwindle by 200 million hectares—about five times the area of California—and lumberjacks will regularly shave about 40% of forests. Along the other, however, farmers and foresters will intensify production and shrink their footprint. Forests will spread anew to more than 200 million hectares, and only 12% of forestlands will hear cries of "timber." This vision for a Great Restoration is realistic—one that the right domestic and foreign policies can secure. The focus is on the year 2050. That may seem distant, but trees grow slowly, and capital-intensive logging firms adjust their practices gradually. In one decade—the time frame for most foreign policies—little change can appear. But five decades' work, with steady guidance, will make the restoration of the forests truly great.

SMART FOOD

Many different forces, including urban sprawl, pollution, and fire, can diminish forests. But around the world, agriculture and timber cutting do much of the clearing. Farmers are usually cited as forests' primary foes. As Time's millennial Earth Day issue lamented, "agriculture is the world's biggest cause of deforestation."

Just how much land is actually needed for agriculture integrates several variables: the size of the population, its income and diet, and the yield of crops grown. Already, growth in human numbers is slowing—the present population growth rate of 1.3% per year has declined steadily from a peak of more than 2% around 1970. Still, by 2050, the total population will have increased, perhaps to as much as 8 or 10 billion. Taming population growth further will likely lessen the threat to forests, but protecting the forests seems only a marginal addition to the impetus for population reduction.

Rising income, meanwhile, has raised the population's demand for food, multiplying the effect of its growing numbers. The rich eat more than do the poor. But the main effect of income growth has been to add meat to many diets. And in terms of land used, eating animals that eat plants is less efficient than eating plants directly. As a rule of thumb, a vegetarian diet requires about 3,000 primary calories daily. Meat-eaters consume twice that amount. Vegetarian diets could therefore markedly reduce the land required to grow food. But secretaries of state are unlikely to convince carnivores to switch from T-bones to tofu.

Given the difficulty in changing population and diet, the best way to reduce food's impact on forests will be to change the fourth factor: how farmers grow crops. Yield—the amount of crops produced per hectare of land—is the key indicator. Over the last quarter-century, average yields of cereal grains, including maize, rice, and wheat, rose 1.8% each year worldwide. Some countries achieved dismal results—yields rose only 0.8% per year in developing Africa and actually declined in Angola, Malawi, and Zimbabwe. Other countries, big ones, outpaced the pack. Yields rose an average of 2.5% annually in Indonesia and more than 3% yearly in China. These gains allowed the worldwide food supply to nearly double, while cropland expanded less than 10%. In India, rising yields almost entirely offset increasing demand for cropland, so the area under cultivation barely changed.

The conventional wisdom, the "Skinhead Earth" scenario, holds that as much as 200 million hectares of forest will be lost in the next decades as agriculture extends to feed larger and richer populations. Current trends, however, suggest not balding but regrowth. If farmers sustain the 1.8% annual yield improvement they have achieved in recent decades, they could meet the growing demand for primary calories while releasing 200 million hectares of cropland.

But farmers can do even better than that and offer even more land to the trees. The authors' research with Paul Waggoner of the Connecticut Agriculture Experiment Station has shown that, with some extra effort, an increase in yield of 2% per year—a plausible goal—could spare a total of 400 million hectares. In other words, today's farmland could be cut by more than a quarter through smarter agricultural techniques. Sustaining a 2% rate of increase will not be easy, but history and technology suggest it can be done. Since sustained efforts to raise U.S. yields began in the 1940s, average yields for wheat and soybeans have almost tripled and corn yields have more than quadrupled. And farmers have hardly tapped the full potential. Champion American corn growers have lifted yields well above 20 tons per hectare without irrigation. Meanwhile, average U.S. corn yields stand at only 8 tons per hectare, and average world corn yields are a meager 4 tons.

How many of the hundreds of millions of hectares that farmers can spare will revert to trees? The amount depends on where cropland is abandoned and how people choose to use it. One and a half centuries ago, farmers had deforested two-thirds of Connecticut. Once they abandoned their farms to build guns and aircraft engines and sell insurance, however, the forests gradually recovered the landscape. But free land does not always become forest. In South Dakota, abandoned farms become grass prairies, not woodlands. Worldwide, no sure equation links the liberation of cropland to the return of trees. Guessing moderately, however, about half the land freed might eventually revert to forest—say, 200 million hectares, or three times the size of Texas and four times the size of Spain.

FAST FORESTS

Farmers may no longer pose much threat to forests. But what about lumberjacks? As with food, the area of land needed for wood is a multiple of population, income, "diet," and yield. The appropriate focus is on industrial wood—logs cut for lumber, plywood, and pulp for paper. Although trees are also cut for fuel, most fuel wood is thinned from hedgerows, shrubs, and other open sources—not forests.

Again, of the relevant factors, strategies to save the forests should not emphasize limiting population and income. Those government agencies and nongovernmental organizations (NGOS) most concerned with forests have little leverage over the number of people, and societies should aim to expand, not shrink, their incomes.

That leaves "diet" and yields. The wood "diet" required to nourish an economy is determined by the tastes and actions of consumers and by the efficiency with which millers transform virgin wood into useful products. Changing tastes and technological advances are already lightening pressure on forests. Concrete, steel, and plastics have replaced much of the wood once used in railroad ties, house walls, and flooring. Genes, silicon, and even ceramics—not boards—are the growth materials for the new economy. Demand for lumber has become sluggish, and in the last decade, with the implosion of the wood-intensive Russian economy, world consumption of boards and plywood has actually declined.

But the appetite for "pulpwood"—logs that are chipped, softened into pulp, and then drawn into sheets of paper and board—is still climbing, driven by the 5% annual rise in pulp consumption in developing countries. Pulpwood accounts for more than a quarter of industrial wood consumption. Paperwork proliferates in developing countries, and inside the glass and steel shells of the new economy, information machines still consume paper voraciously. Reliable electronic archives and electronic books will eventually quiet the taste for paper. So far, however, life still requires hard copy.

Meanwhile, more efficient lumber and paper milling is already carving more value from the trees we cut. Because waste is costly, the best mills—operating under tight environmental regulations and the gaze of demanding shareholders—already make use of nearly the entire log. In the United States, for example, leftovers from lumber mills account for more than a third of the wood chips that are turned into pulp and paper; what is still left after that is burned for power. And further improvements in management and technology will squeeze even higher value out of products and spare more virgin wood. In British Columbia, since the mid 1980s, sawmills have lifted the lumber obtained per cubic meter of log at an average rate of 1.2% per year. Worldwide, the pulp and paper industry is shifting a significant share of production from chemical to mechanical pulping, which cuts the wood required for a ton of useful pulp by half. And recycling has helped close leaks in the paper cycle. In 1970, consumers recycled less than one-fifth of their paper; today, the world average is double that.

New engineering has also helped decouple demand for virgin wood from the swelling population and economy. For example, floor systems built from engineered wooden I-beams use about one-quarter less fiber than traditional construction with solid rectangular ribs. And as a substitute for plywood, millers make oriented strand board (OSB) by gluing wood flakes in perpendicular layers. OSB can be manufactured from small trees, and it consumes the whole tree, except for bark and limbs. By contrast, plywood mills—which peel timber into sheets and glue them together like cream cookies—work only with larger trees and leave an unpeeled core at the center of every log.

As this suggests, the wood products industry has learned to increase its revenue while moderating its consumption of trees. This is not surprising, for efforts to lower trade barriers and improve management of forest resources are increasingly exposing millers worldwide to prices, competition, and consumer requirements that are spreading innovation and efficiency more widely. Large, capital-intensive pulp and paper mills are already responding—their investors demand it. But in much of the world, sawmills thrive on remoteness, trade barriers, and artificially cheap logs that shield them from competition. By one estimate, 3,000 sawmills in Argentina function with an average input of only 1,000 cubic meters of wood per year. At such small scales—less than one-hundredth the size of the most modern sawmills—millers can hardly implement the most efficient practices.

Demand for industrial wood, now about 1.5 billion cubic meters per year, has risen only 1% annually since 1960 while the world economy has multiplied at nearly four times that rate. Conventional wisdom predicts that the total amount of wood harvested will reach 2.5 billion cubic meters in 2050. But the figure could be much lower if millers improve their efficiency, manufacturers deliver higher value through the better engineering of wood products, and consumers recycle and replace more. Together, these steps could shrink demand to about 2 billion cubic meters per year and thus reduce the area of forests cut for lumber and paper.

As with agriculture, yield—cubic meters of wood grown per hectare of forest each year—provides the largest leverage for change. Historically, forestry has been a classic primary industry; like fishers and hunters, foresters have exhausted local resources and then moved on, returning only if trees regenerated on their own. Most of the world's forests still deliver wood this way, with an average annual yield of perhaps two cubic meters of wood per hectare. If yield remains at that rate, as illustrated, by 2050 lumberjacks will regularly saw nearly half the world's forests. That is a dismal vision—a chainsaw every other hectare.

Lifting yields, however, will spare more forests. Raising average yields 2% per year would lift growth over 5 cubic meters per hectare by 2050 and shrink production forests to just about 12% of all woodlands—the Great Restoration.

Industry has already taken big steps along the restoration path by sowing intensively managed "plantation" forests that act as wood farms. According to the U.N. Food and Agriculture Organization (FAO), one-quarter of industrial wood already comes from such farms, and the share is poised to soar once recently planted forests mature. At likely planting rates, at least one billion cubic meters of wood—half the world's supply—could come from plantations by the year 2050. Seminatural forests—for example, those that regenerate naturally but are thinned for higher yield—could supply most of the rest. Small-scale traditional "community forestry" could also deliver a small fraction of industrial wood. Such arrangements, in which forest dwellers, often indigenous peoples, earn revenue from commercial timber, can provide essential protection to woodlands and their inhabitants.

Changes in both markets and regulation explain the shift toward high-yield, land-sparing forestry. Supply from "old-growth" forests—mature natural forests dominated by large, old trees—is tightening while the relative costs of trees from plantations are falling. In Oregon, for example, public pressure and laws to protect endangered species have reduced felling on federal lands by four-fifths since the mid-1980s. Offsetting that shrinking supply is rising production on private land in the southern United States—where sunlight, moisture, and good soils for forests abound. Today, the American South—which Bruce Zobel of North Carolina State University called the "wood basket of the world"—supplies 15% of the world's industrial timber, at a sustainable average yield of about 5 cubic meters per hectare.

Outside the United States, diminished access to traditional sources of virgin wood and the need to control wood costs are also concentrating production. In British Columbia, where most forests are old growth, regulators have reduced the allowable cut by nearly a third over the last two decades, and more restrictions are likely. Clark Binkley, former dean of the University of British Columbia's School of Forestry, has argued that the province's logging can remain competitive only by shrinking its footprint and raising yields to twice or three times the current average annual yield of 2.2 cubic meters per hectare. In Brazil last year, the government and a coalition of 189 environmental groups scuttled a plan to open half the Amazon forest for potential clearing. Meanwhile, nearly all new Brazilian industrial wood comes from high-yielding plantations in the country's southeast, outside the

Amazon region. China has reduced cutting of natural forests by a fifth since 1995. Malaysia and Indonesia, dominant exporters of tropical old-growth logs, have both announced reductions that could halve felling in their ancient forests by 2010. New plantations in those countries will not mature in time to fill the gap, but planted forests in New Zealand, Chile, and elsewhere stand ready to deliver. Chile alone will earn $3 billion in foreign exchange this year from forest products, nearly all grown on plantations that cover only 3% of Chilean territory. Trade is rationalizing world wood production toward the highest—and most land-sparing—yields.

With economics already favoring intensive production, foresters should be able to lift the average world yield in lumbered forests to 5 cubic meters per hectare by 2050. A recent study compiled by Wood Resources International, the World Bank, and the World Wildlife Fund (WWF) suggests that more than a fifth of the world's virgin wood is already produced from forests with yields above 7 cubic meters per hectare. And foresters have only begun to tap the potential for high growth. Roger Sedjo at Resources for the Future has documented that economically competitive plantations in Brazil, Chile, and New Zealand can sustain yearly growth of more than 20 cubic meters per hectare with pine trees. Aracruz Cellulose, Brazil's top planter of eucalyptus—a hardwood good for some papers—has invested heavily in forestry research that now delivers an extraordinary average of 43 cubic meters per hectare. In the Pacific Northwest and British Columbia, with plentiful rainfall, hybrid poplars deliver 50 cubic meters per hectare. And under extreme conditions—with irrigation, fertilization, and intensive pest controls—eucalyptus has been clocked at 100 cubic meters per hectare (or 20 times the goal of 5 cubic meters by 2050).

Foresters can push trees even faster. Today, the most advanced tree-breeding programs are only in their second, third, or fourth generations, since trees, unlike annual wheat and maize, are slow to reach sexual maturity. Modern biology can already speed breeding, however, by spotting the genes for superior performance early and then growing plants with those traits through traditional methods. Genetic engineering, now in its infancy, will be able to insert or delete selected genes directly and should gradually gain acceptance. Big tree planters—such as Westvaco Corporation—are already placing large bets on biotechnology, which promises to boost the economic advantage of plantation forestry. Having spent heavily on state-of-the-art mills and to select and rejigger tree genes, the forest industry has come to prefer planted forests, which let it control what stock grows where.

Economists, environmentalists, and people who live in the woods have all raised warning flags about intensive industrial forestry. Some worry that plantation forestry is prone to fail because much of it depends on wasteful government subsidies. Indeed, public funds have helped establish viable land-sparing plantations—just as they helped initiate other new waves of industry, including jet travel and the Internet. Three-quarters of South American plantations were planted after countries adopted incentive schemes, usually subsidies. Yet today, the private establishment of new plantations is continuing despite the fact that governments are scaling back incentive programs.

Another source of concern has been the profitability of private investment in these industries. A recent PricewaterhouseCoopers study found that the 50 largest global forestry companies earned, on average, a paltry 4.1% return on capital investments. Over-capacity in the industry and vast potential supplies of wood from poorly regulated forests have undercut prices and hurt the performance of even the best-run firms. A history of poor returns makes it hard for the forest industry to raise still more money to continue the shift to high-yield wood production. The current consolidation of the timber industry, however, will help surviving firms win new investors. Government efforts to improvement management and restrict cutting of natural forests will also favor modern industry, which has a smaller footprint.

Environmentalists nevertheless worry that industrial plantations will deplete nutrients and water in the soil and produce a vulnerable monoculture of trees where a rich diversity of species should prevail. Meanwhile, advocates for indigenous peoples, who have witnessed the harm caused by crude industrial logging of natural forests, warn that plantations will dislocate forest dwellers and upset local economies. Pressure from these groups helps explain why the best practices in plantation forestry now stress the protection of environmental quality and human rights—and why large firms, with the most exposure to pressure, are generally the most scrupulous. In Sweden, for example, large industrial forest owners aim to follow strict codes of conduct that respect the traditional practices of indigenous peoples, whereas smaller landowners still tend to fence the reindeer-herding Saami people out of their traditional grazing grounds.

As with most innovations, achieving the promise of high-yield forestry will require feedback from a watchful public. Public scrutiny will help industry to make the new technologies socially acceptable. The main benefit of the new approach to forests will not reside within the planted woods, however. It will lie elsewhere: in the trees spared by more efficient forestry. An industry that draws from planted forests rather than cutting from the wild will disturb only one-fifth or less of the area for the same volume of wood. Instead of logging half the world's forests, humanity can leave almost 90% of them minimally disturbed. And nearly all new tree plantations are established on abandoned croplands, which are already abundant and accessible.

FOREST-FRIENDLY FOREIGN POLICY

Actors in the wood drama can thus take three basic approaches to preserving and restoring the world's forests: lifting crop yields, choosing value over volume in making wood products, and concentrating forestry in fast-growing wood farms. Together, these measures can increase to 3 billion hectares the area of forests that are left for nature, the protection of watersheds and indigenous peoples, and other non-industrial uses. In contrast, the "Skinhead Earth" scenario will shrink these non-industrial forests to 1.8 billion hectares. This difference—1.2 billion hectares—is almost twice the area of the Amazon Basin. One central question remains, however: How can foreign policy help farmers, foresters, millers, and consumers do their part?

Much useful activity is already under way. Environmental NGOs around the globe have organized behind forest protection. All major forestry firms now participate in various activities to lessen the environmental harms of forestry. Multilateral development funders such as the World Bank have added the protection of forests and their role in alleviating human poverty to their agendas. The United Nations engages forestry issues through the FAO and the ongoing effort to implement commitments made at the 1992 Earth Summit in Rio de Janeiro (at which forestry policies were hotly contested). Since Rio, an alphabet soup of panels, forums, and task forces on forests have filled U.N. meeting rooms. This year, the U.N. launched an annual Forum on Forests to provide an outlet for the many clamoring voices. Forests do not suffer from a lack of attention in international politics.

The problem is the absence of a clear and widely shared goal to guide policy. Because the U.N. framework includes all nations, forest agendas are confused and exceedingly complex, and progress is measured by the placement of commas and clauses. Worse, since Rio, the central debate has been whether and how to negotiate a legally binding forest treaty. Experience in managing other international environmental problems shows that binding treaties work best when they include detailed commitments with which governments can comply. A binding instrument is ill suited to forests, however, because governments—and the people they represent—do not yet share a vision for how to protect the world's woodlands. Moreover, detailed actions would necessarily vary by country and be extremely difficult to codify into a single international law. Key elements of a sensible coherent vision—such as lifting grain and forest yields—are impossible to plan top-down by regulatory treaty.

A better approach would begin by adopting a nonbinding but clear, quantitative, measurable goal: namely, a forest estate expanded by 200 million hectares in 2050 and in which a smart, sustainable forestry industry concentrates on little more than 10% of the forested area. This "90:10" vision would serve to anchor and focus a bottom-up process through which governments and stakeholders—individually and collectively—would explore the actions they must take to achieve their goal by 2050. Responses could then vary as necessary. Some countries, such as Brazil and Indonesia, could conclude that the best way they can contribute trees to the world balance sheet is by improving the regulation of their public lands. Others, such as Chile and New Zealand, could do their part by striving to become industrial wood baskets. Still others, such as Russia, could focus on improving forest institutions. Sten Nilsson of the International Institute for Applied Systems Analysis has shown that Russia has great potential to spare trees by exposing the forest sector to modern market discipline and regulation.

A bottom-up process is needed because no single set of policy instruments is appropriate to all settings. Factors such as land ownership vary widely. In the United States and most of western Europe, for example, forests are held mainly in private hands. The United States alone has ten million forest owners. Most U.S. industrial wood comes from private land, and ownership fragments when inheritance splits wood tracts among offspring. In this setting, improving environmental standards in wood production has required certification schemes that are compatible with private land ownership. Programs such as the voluntary "Tree Farm" system of standards have succeeded in engaging owners of small forest parcels who are wary of costly production standards that only large landowners can afford. By contrast, in Canada and many developing countries, governments own forests and use concessions to control cutting. In such settings, policies should focus on setting the right standards for granting concessions and on the firms that do the cutting.

Measuring progress will require a better system for tracking and assessment. Data on forest cover already abound, but reliability varies by country, as do definitions of terms as fundamental as "forest." Information on key elements, such as changes in crop and timber yields and production areas, is fitfully reported in many places. All but a few countries lack data and analysis of milling efficiency. Private groups, especially commercial firms, could fill the gaps. But so far they have had little incentive to do so because no guiding forest vision has informed and focused the policy debate.

In other examples of international environmental cooperation—such as cleaning up the North Sea or combating acid rain in Europe—clear, ambitious, and achievable visions backed by data systems have proven to be key to success. In those cases, as in forestry today, governments were at first uncertain what they could achieve but were keen to make an effort. Nonbinding legal frameworks, along with periodic performance reviews, facilitated action and learning. Only when governments had come to understand what commitments they could realistically implement did they establish binding treaties to lock in progress.

THE FOREST 14

An effective diplomatic strategy for restoring forests will require adjusting conventional wisdom and updating existing institutions. Leadership by a set of key countries could substantially ease the task: Australia, Brazil, Canada, China, Finland, India, Indonesia, Japan, Malaysia, New Zealand, Russia, South Africa, Sweden, and the United States. These "Forest 14" control two-thirds of the world's woodlands and span diverse forest types and management strategies, from intense plantations (New Zealand and South Africa) to mixed use (China, India, and the United States) to large old-growth harvesters (Indonesia and Russia). They include major exporters (Canada and Malaysia), the world's largest importer of forest products (Japan), and a variety of consumer needs and preferences. The list encompasses forest hegemons of every region, and the behavior of governments, firms, and NGOs in these nations sets world standards in forestry.

The Forest 14 do not correspond to any existing and effective international institution, so one question will be how to convene them. The Group of 8 (G-8) might act as a catalyst. It includes 4 of the Forest 14 (Canada, Japan, Russia, and the United States), and its other members (France, Germany, Italy, and the United Kingdom) feel strong public pressure to protect forests. Already, the organization has focused on forest topics such as illegal logging and counterproductive subsidies. Moreover, the G-8 is the only high-profile international forum—other than the more inclusive International Monetary Fund (IMF), World Bank, and U.N.—that engages Russia, the world's most forested nation, on topics important to Moscow. And the G-8 also has experience engaging developing countries—as became evident last year with the creation of the larger G-20 to discuss key global financial and economic issues. The G-8 does not have the built-in means to analyze forest issues, but the Forest 14 could enlist its members and other partners such as the World Bank-WWF Forest Alliance to sponsor studies in their areas of comparative advantage—a practice used effectively for other kinds of international environmental cooperation. Topics would include lifting grain yields, setting goals and requirements for high-yield forest plantations, crafting strategies for increasing the efficiency of milling, examining the potential for recycling and substituting other materials for wood, creating programs to raise the regulatory capacity needed to stem illegal logging, and eliminating subsidies that perversely effect wood production and use.

As the stakeholders debate the vision of a Great Restoration, they will clarify the needed complementary policies and programs. One such requirement is better strategies for dealing with the vast areas that lie "in the middle"—lands that are not under intensive cultivation or wood production but are also not formal, strictly protected nature areas. To date, much of the debate over protecting forests and wilderness has focused on formally demarcated and legally protected areas. Such protection rightly safeguards Earth's greatest forest treasures, but formal protection holds little promise for most of the world's woodlands. Today, only about 8% of world's forests are formally protected in parks. Many governments hesitate to expand formal protection, for fear of locking away land that might serve other purposes. In many settings, forest dwellers also resist "protecting" their forests because well-meaning but ham-fisted governments have tried to secure forests in their natural state by banning longstanding local practices such as hunting and small-scale forestry.

Another critical need is to find ways to assign economic value to standing forests (other than as cut timber). Most of the world's untouched frontier forest is still protected by economic factors—remote locations and unfavorable terrain keep farmers and lumberjacks at a distance. But threats multiply where roads and rails penetrate, bringing saws to trees and timber to markets. Revenue from ecotourism may help preserve forests, as might schemes to value forests' contribution to the ecosystem (such as their climate-cooling sequestration of carbon).

COMMON CAUSE

For the great restoration to succeed, farmers, foresters, and environmentalists must recognize their common interest in high-yield production. Those concerned with forests have traditionally viewed farmers as part of the problem. But by lifting yields, farmers can be part of the solution. Brussels and Washington can help matters by paying farmers to grow forests instead of paying them not to grow food. Meanwhile, foresters are wary of environmentalists who, they fear, seek to make forestry unprofitable and to fence off every parcel of land that can be freed from production. Environmentalists, in turn, accuse foresters of destroying diversity, polluting the land, and displacing local people. But Big Timber and Big Green can and must learn to meet each other's core concerns.

The conflict between these groups is especially evident in the effort launched by the environmental community—and by some forest-products companies, mainly in Sweden, that already meet extremely tight environmental standards—to certify wood that is produced "sustainably." So far, only a tiny fraction of production forests have been so certified, and most consumers have refused to pay extra for "green" wood. But certification is gathering force; standards established over the next few years may lock in forest practices for decades. These standards should be set with the path to long-term restoration in mind. In principle, the leading certification system—the Forest Stewardship Council—is compatible with such a goal, but efforts are needed to demonstrate that economically feasible certification can favor high-yield growth. Certification that favors low-yield strategies may produce a happy tree but lead to a small forest.

The certification debate underscores the fact that no single approach is enough for achieving the Restoration by 2050. Policy must exert leverage in all areas: adopting new technologies and practices to improve forestry and agriculture, building a better information system, and launching a bottom-up process for translating the grand vision of the Great Restoration into detailed strategies. Realistically, one cannot expect all nations to come on board at once. But surely 14 countries can take the process seriously. With them in the lead, the rest will follow.

Although 2050 remains distant, most elements of the plan need to be put in place in half that time—by 2025. Trees are slow growers, and so the saplings that will deliver nearly all the 2 billion cubic meters of wood needed in 2050 must start growing 20 to 25 years earlier. The year 2040 might suffice as a start date for some fast-growing trees (such as eucalyptus and poplar), but even plantations of those trees will require investments in mills and other assets that are best planned and built gradually and well in advance.

To achieve all of this by 2025 will require meeting even more immediate goals. Over the next five years, the Forest 14 should adopt a draft strategy along the lines laid out above, which will help focus subsequent debates over policy. And they must start the decade-long process of building the data collection and analysis system necessary for bottom-up assessments of national forest policies. In parallel, they should start measuring overall progress. Will demand for cut wood really reach 2 billion cubic meters by 2050? If wood consumption does not level out at 2 billion cubic meters per year—perhaps because of rising demand for paper—can foresters lift yields more rapidly to compensate? Are crop yields rising at the 2% per year needed to liberate 200 million hectares of agricultural land for forests? Are wood yields rising rapidly enough so that the planted forests of 2025 will average 5 cubic meters' growth per hectare? Are forestry firms expanding plantations at about 2% per year—a rate consistent with historical patterns and sufficiently rapid to deliver enough planted wood by 2050? Are countries implementing policies to help the liberated land recover and to protect the forests still not cut?

News reports and publicity along the way can help realize the vision. Benchmarks set and accomplishments achieved should be well publicized to make the reality and significance of the Great Restoration apparent to all. Within the next decade, the 14 nations that lead the effort should manage to achieve no net loss in their forests. Some cutting of natural woods may continue, but it will be offset by resurgent forests growing on liberated farm and timber lands. By 2025, the Forest 14 can promise that there will be no more loss of natural forests, including the large tracts of frontier forests that are nature's vital legacy.

Neither feeding the world population nor supplying timber and pulp requires the world forest estate to shrink, as it has ever since ancient civilizations felled their forests to smelt, build, heat, and cook. Rather, while profitably meeting growing demand for wood products, humanity can vastly increase the area of forests and simultaneously reduce the amount of those forests that is disturbed. Such a Great Restoration is truly a worthy goal for the landscape of the new millennium.

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www.fsl.orst.edu/tgerc/iufro2001/eprocd.pdf

Biotechnology and the Forest Products Industry

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ABSTRACT

Forest biotechnology has great potential to produce important benefits for the forest products industry and the general public. Benefits to industry may include higher value raw materials, lower manufacturing costs, and further improvements in environmental performance. Potential public benefits include new supplies of renewable energy and materials; effective new options for solving difficult problems in environmental management and ecological restoration; and new opportunities for employment and sustainable development in an industry based on renewable resources. The potential benefits of forest biotechnology justify accelerated efforts to advance the underlying science; develop and test promising applications; evaluate ecological risks and social concerns; and develop appropriate policy frameworks.

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The forest products industry is large and complex. It employs millions of people with diverse skills at locations around the world. The industry's products (Table 1) help meet important human needs for such things as housing, information, packaging, and personal hygiene.

There are good reasons for optimism about the future of the forest products industry. World demand for forest products will increase substantially with increases in population and economic prosperity. Moreover, wood has inherent environmental advantages relative to other raw materials. For example:

- Economic demand for wood provides important incentives for afforestation, reforestation, and sustainable forest management.
- Most products made from wood are renewable, recyclable, and require less fossil energy to manufacture than competing materials.
- Residuals from wood processing are important sources of renewable energy. The forest products industry is already the world leader in biomass energy production, and will probably increase its production substantially if new technologies (e.g., biomass gasification) are successful.

Optimism about the industry's future is tempered by serious challenges. The land base for future wood production will be constrained severely by competing land uses (e.g., agriculture, residential development, and wilderness). In addition, the industry is contending with dynamic and difficult market conditions; a large and growing number of government regulations with major impacts on the industry; and important stakeholder initiatives such as forest certification.

The industry's wood supply challenge can be overcome by increasing production on lands well suited to intensive silviculture and by developing landscape management strategies that improve the overall condition of forest ecosystems. Forest managers are making substantial progress in these directions by implementing technologies such as tree improvement, weed control, wildlife manage-

Table 1. Examples of forest products that help meet important human needs.

Forest Resources
- sawlogs, pulpwood, fuel wood
- recreation opportunities
- ecosystem services such as water purification, carbon sequestration, wildlife habitat

Building Materials
- framing lumber, structural panels, siding, beams, floor joists, roof trusses, interior paneling
- paper components of wall board, counters, and insulation

Communication Papers
- books, newspapers, magazines
- office papers, stationary, school and note pads, drawing paper
- greeting cards, poster and display boards

Packaging
- boxes, bags, drums, tubes, spools, cores
- paperboard for food packaging, milk cartons, juice cartons
- pallets, wood shipping containers

Tissue and Absorbent Fibers
- personal hygiene products
- paper towels
- diapers
- convalescent bed pads

Specialty Cellulose
- acetate textile fibers
- photographic films
- plastics, pharmaceuticals, food products
- thickeners for oil drilling muds
- rayon for tires and industrial hoses

Other Forest Products
- steam & electricity from biomass fuels
- Christmas trees
- envelopes, labels, file folders
- toys, decorations, sporting goods
- mulch, compost, wood ash, and other soil amendments
- railroad ties, utility poles
- landscaping timbers, fence posts
- disposable cups & plates, take-out food containers
- furniture, tool handles, musical instruments
- specialty chemicals, fragrances

ment, landscape design, and many others. Effective integration of technology options with economic, ecological, and social objectives is one of the forest industry's top priorities and the essence of sustainable forestry.

Manufacturing facilities in the forest products industry are technologically diverse and operate in many different countries, climates, and markets. General concerns include high capital costs, low commodity prices, and a complex array of environmental and energy issues. The industry has made substantial progress in environmental and energy performance, but still faces major challenges in these areas.

Biotechnology can help the forest products industry overcome some of its most important challenges. In this paper, we describe benefits of potential biotech applications in the industry's forestry and manufacturing operations. We also discuss obstacles to progress in forest biotechnology generally and some promising paths forward.

BIOTECHNOLOGY AND TREE IMPROVEMENT

The productivity and quality of agricultural crops have been greatly improved by centuries of breeding, testing, and genetic selection. Modern crop varieties are much better sources of food and fiber than their wild ancestors, and they greatly reduce the amount of land that must be cultivated to meet human needs.

In comparison to agricultural crops, trees planted for wood production are wild, undomesticated plants. Most efforts to improve trees for wood production have been underway for less than 50 years. Initial results are scientifically and economically important, and they confirm expectations based on agricultural experience that tree species have enormous genetic potential that could be expressed in valuable new varieties.

Progress in forest tree improvement has been constrained by various difficulties inherent in tree breeding and propagation. These include (a) need for multi-year progeny tests; (b) multi-year delays from seed germination to flowering; (c) self incompatibility in important species (no inbred lines); and (d) biological and economic obstacles to large-scale vegetative propagation of superior lines (especially in conifers).

Biotechnology has great potential to accelerate tree improvement and enable production of higher-value raw materials for the forest products industry. Key technologies include (a) advanced breeding strategies based on marker-aided selection; (b) improvements in vegetative propagation based on somatic embryogenesis and/or organogenesis; and (c) rapid introduction of valuable traits into superior germplasm by genetic engineering.

Acceleration of tree improvement through biotechnology will enable substantial increases in tree growth rates on sites close to mills. When ready for harvest, these sites will yield large numbers of uniform stems per hectare. High yields will reduce harvesting costs and the area of forest land required to meet mill demands for raw material. Short-haul distances to mills will reduce log transportation costs. Efficiencies in harvesting and transportation will reduce fossil fuel consumption and CO_2 emissions associated with raw material acquisition.

Faster growth is important, but is only one of the potential benefits of accelerated tree improvement via biotechnology. For example, new tree varieties with special wood properties will enable more rapid development of raw material supplies tailored to the requirements of manufacturing processes. Improvements in raw material quality will allow mills to reduce manufacturing costs and improve product quality. See Table 2 for examples.

Table 2. Examples of wood quality improvements and benefits that might be achieved through biotechnology.

Wood quality improvements	Potential benefits
Smaller core of juvenile wood	Greater lumber strength and stability
Higher specific gravity	Higher pulp yields relative to inputs of energy and chemicals in the pulp mill
Lower lignin content	Reduced inputs of chemicals and energy in pulp bleaching

Many other benefits from biotechnology and tree breeding are possible. For example:

- Pest management strategies based on improvements in the genetic resistance of trees and reduced quantities of insecticides and fungicides.
- Ecological restoration strategies enabled by genetic engineering of tree species devastated by exotic diseases (e.g., American chestnut).
- Carbon sequestration, soil reclamation, and bioremediation strategies enabled by new trees capable of tolerating poor soil conditions such as drought and chemical contamination.
- New strategies for sustainable production of valuable chemicals in trees based on genetic engineering of secondary metabolic pathways.

BIOTECHNOLOGY AND FOREST PRODUCTS MANUFACTURING

The forest products industry is under great financial pressure at present. Overall returns to shareholders have been disappointing for various reasons—most notably high capital costs (especially in the pulp and paper sector) and intense price competition in the industry's commodity markets. Disappointing financial returns, coupled with general economic globalization, are driving a dramatic restructuring of the industry. Mergers and acquisitions are producing a few global-scale competitors and creating niches for new smaller-scale companies.

Although financial and market issues are dominant near-term concerns, industry leaders have keen interests in the potential of technology to reduce manufacturing costs and create new products. Biotechnology in particular has enormous potential. In addition to improving the quality and quantity of raw material supplies, biotechnology could have radical impacts on pulping processes, waste-to-energy systems, and other aspects of forest products manufacturing. For example:

- Biotechnology could enable the development of new pulping processes based on selective enzymatic cleavage of lignin polymers. Potential benefits include lower capital costs, higher product quality, and lower consumption of both chemicals and energy.
- Biotechnology could enable the development of new systems for converting organic residuals into bioenergy. Potential benefits include lower costs for solid waste management and reduced need for fossil energy.

REALIZING THE POTENTIAL OF FOREST BIOTECHNOLOGY

During the past century, the forest sector has made great progress in developing better systems for growing and harvesting trees, making and distributing products, and reducing environmental impacts. Progress has been enabled by research, development, and integration of technologies as diverse as forest regeneration, landscape management, chemical and material recycling, and biological treatment of wastewater.

Biotechnology is poised to make significant contributions in various systems in the forest sector. Realizing the great potential of forest biotechnology will be an enormous and exciting challenge. The rate of progress will depend on science and technology factors interacting with social, economic, and political issues.

Inadequate government support for pre-competitive research is an important obstacle to progress in forest biotechnology. Through its Agenda 2020 program, the forest products industry has suggested priorities for pre-competitive research and provided funding for several projects in partnership with the U.S. Department of Energy and the Forest Service (Table 3).

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Table 3. Forest biotechnology projects supported through Agenda 2020.

Principal Investigator	Project title	Lead institution
Brunner	Dominant negative mutations of floral genes for engineering sterility	Oregon State University
Chang	Exploiting genetic variation of fiber components and morphology in juvenile loblolly pine	North Carolina State University
Davis	Molecular physiology of nitrogen allocation in poplar	University of Florida
Davis	Molecular determinants of carbon sink strength in wood	University of Florida
Li	Search for major genes using progeny test data to accelerate development of superior loblolly pine plantations	North Carolina State University
Neale	Genetic marker and quantitative trait loci mapping for wood quality traits in loblolly pine and hybrid poplars	USDA Forest Service
Peter	Accelerated stem growth rates and improved fiber properties of loblolly pine	Institute of Paper Science & Technology
Pullman	Trees containing built-in pulping catalysts	Institute of Paper Science & Technology
Tsai	Genetic augmentation of syringyl lignin in low-lignin aspen trees	Michigan Technological University
Tschaplinski	Biochemical and molecular regulation of crown architecture	Oak Ridge National Lab
Tuskan	Marker-aided selection for wood properties in loblolly & hybrid poplar	Oak Ridge National Lab
Whetten	Pine gene discovery project	North Carolina State University
Williams	QTL and candidate genes for growth traits in *Pinus taeda* L.	Texas A&M University

Agenda 2020 and other programs are supporting valuable projects, but the low overall level of funding for pre-competitive research is a critical limiting factor in forest biotechnology. Mapping the genomes of model tree species and discovering molecular controls of key processes such as wood formation are formidable tasks that will take decades at current rates of progress. A major initiative is needed to accelerate pre-competitive research in these areas.

The ecological, social, and policy issues associated with forest biotechnology are complex and extremely important. Informed discussions, research, and collaborations involving diverse parties are needed to better define issues and potential solutions. The new Institute of Forest Biotechnology (www.forestbiotech.org) will have an important role in bringing diverse parties together and organizing necessary activities.

CONCLUSIONS

Forest biotechnology holds important opportunities and challenges for the forest products industry. The industry's technology leaders appreciate the economic potential of forest biotechnology and have diverse views on critical issues such as time to commercialization and risk management strategies.

The future of biotechnology and its value to the forest products industry will be affected greatly by public perceptions of social and ecological issues. We believe the potential benefits of forest biotechnology justify greater public support for pre-competitive research to advance the science; develop and test promising applications; evaluate ecological risks and social concerns; and develop appropriate policy frameworks.

In this paper, we have outlined some promising applications of forest biotechnology with emphasis on their possible value to the forest products industry. Potential benefits to the public are also substantial. They include (a) new supplies of renewable energy and materials; (b) effective new options for solving difficult problems in environmental management and ecological restoration; and (c) new opportunities for employment and sustainable development in an industry based on renewable resources.

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Responding to New Trees and to the Issues at Hand: The Institute of Forest Biotechnology

W. Steven Burke

ABSTRACT

Effective and thoughtful development, application, and acceptance of complex new technologies require many steps and participants. The movement from science and research to products and public impels attention to three areas simultaneously: to science and research; to industry and products; and to a richly complicated mixture of societal, ethical, environmental, regulatory, and public issues. The academic and industrial forest endeavor, historically not technology-intensive, is brought to new challenges by the process and issues of biotechnology development. Application of biotechnology to trees and forests is, moreover, particularly challenging because of their extraordinary importance to human development, culture, values, and economies; trees are, after all, the only plant or crop to which large numbers of people have routinely ascribed moral value. As a result, a full and rigorous societal dialogue involving all parties attentive *from whatever vantage point* to forest biotechnology—scientists and researchers, industry, public interest groups and ethicists, consumers and policy-makers—is requisite for considered and effective application of the technology to trees. Bringing about such engagement will require new strategies, engagement among parties varying in values and agenda, consensus and shared ground if possible, and sustained effort. Gaining such outcomes will be as important as demanding. The Institute of Forest Biotechnology, a private non-profit corporation, was established in 2000 in Research Triangle Park, North Carolina, to work for this engagement. Not a site for research, the Institute will bring diverse parties together to address—through projects, meetings, and publications—the research, scientific, industry, societal, and economic issues of forest biotechnology worldwide.

Three reasonable assertions offer a framework for thought:

- Trees are the only plant routinely ascribed intrinsic moral value by large numbers of people.
- Biotechnology will change some trees, and be applied worldwide in coming years.
- Trees from technology will seem, to many, manifestly different from trees of tradition.

How can we characterize an endeavor characterized by these—and other, equally complicated—assertions? Why is forest biotechnology so very rich in issues as well as potential, in implications as well as complexity?

How do we feel about trees? How do we feel about transgenic trees?

We know how we feel about trees. Quite sensibly and understandably, we love them, with an atavistic fervor rooted in something not easily defined.

We are perhaps uncertain of our responses to transgenic trees and forest biotechnology, for the endeavor comes new to our attention.

How can we prepare our work, activities, and policies for the increasing development and use of forest biotechnology over coming decades? Doing so is requisite, as forest biotechnology worldwide will prove a complicated combination

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of technology, imperative, and societal issues. Are we ready? How can we think about trees, about forest biotechnology, and about strategies of response?

I offer a framework for our thinking, under four necessarily interrelated headings:

1. Thinking about Technology
2. Thinking about Trees
3. Representative Forest Biotechnology Issues
4. The Newly Established Institute of Forest Biotechnology.

THINKING ABOUT TECHNOLOGY

To consider the trees of technology, we must have a reasonable understanding of technology development, the context in which forest biotechnology grows. Technology development is a process—a continuum—a movement from societal idea and need to product and societal impact. The movement is deliberate, long-term, sequential, and complicated. It can be easily broken down into three main phases:

- *Discovery*, a matter largely of science and research
- *Development,* in the main the realm of industry in free market societies
- *Application,* eventual societal utilization and, we hope, beneficial impact.

A prime question must be very soon addressed towards the end of the discovery phase: what is the likelihood of societal and economic return from further exploration and eventual development of promising research? Return of both sorts is of course requisite, in some balance determined appropriate by varied parties. The forest industry worldwide is, at present, very much engaged in determining whether sufficient return can over time be gained to merit substantial investment in forest biotechnology.

The continuum from discovery to application is a combination of *stages, participants and resources*, and *issues.* It also requires attention to the *context* and *imperative* of biotechnology development.

Eleven Broad Stages

The process involves many different steps, each different in requirements, participants, length, and outcomes. Eleven broad stages are key, largely constant and common, and must be addressed by a combination of vision, funding, activities, and policy. They can be laid out in a suggestive, but not exact, schema.

Science and research, stage 1, provide the requisite foundation. Stage 2, policy and impetus, impels the decision to commit to further development. Technology transfer proves an increasingly crucial stage 3, enabling the movement of promising ideas from the research to the private sectors. In stage 4, application and product possibilities are actively explored, as foundational impetus for stage 5: involvement or formation of companies working to move the possibility to commercial reality. Stage 6 manifests the ongoing imperative, particularly key at this juncture, for sustained usually large investment. In stage 7, testing and trials establish the safety and effectiveness of the new product. Stage 8, is manufacturing or growing. Stage 9 proves increasingly important: adoption by existing companies or intermediates of the new product or application, a decision of use by the food processing or healthcare or pulping industries. Stage 10 reveals final acceptance and use, at the consumer as well as societal levels. Stage 11 is the key juncture that we seem too seldom to address, compelled as we are by the demands of the immediate: charting the future.

It is difficult to imagine an area of biotechnology as demanding of future charting—of a thoughtful and purposeful analysis of the horizon—as forestry and trees.

Participants and Resources

The process and stages of technology development are shaped and moved along by varied persons and entities, private and public. Some participants are directly and always required to move biotechnology from science to product: researchers; universities and laboratories; small and large companies; entrepreneurs and risk-takers; investors; regulators; intermediate users or adopters; trained workers; manufacturers or growers; ethicists; educators; catalysts, policy-makers and committed governments; and accepting users.

Other participants support and facilitate the process. While not required, their presence and thoughtful participation often accelerates results. Among such entities are administrators; technology transfer officers; biotechnology centers or initiatives; incubators and research parks; varied government agencies; policy-makers with a long-term view; experienced managers able to bring experience to a second or third project, company, or technological challenge; and good critics.

Other participants are indirectly involved, or skeptical, or even possibly hostile, but they also shape the process of technology development, for they shape the nature and terms of the movement from science to public. These parties are varied in agenda and approach, and include researchers in other fields; ethicists and philosophers; government agencies; investors and funders varied projects, agencies, and institutions; informed thinkers and uninformed thinkers; questioners; non-government organizations; legislators and policy-makers; other professions; public interest groups; users; and—to our recent consternation, here in the American Northwest, directed to trees—terrorists.

These participants vary enormously in training, values, and expectations—and, as such, in their response to stages, outcomes, and the issues attendant to the process.

Intrinsic Issues

Issues are intrinsic to the process of biotechnology development. Some are expected and follow logically from earlier experience; others are new and largely without precedent. They vary by stage and by participant point of view. They demand our considered attention and should not occasion our surprise. Is it likely that a technology manifestly changing living organisms would not yield issues?

The issues of biotechnology are societal or policy, ethical or personal—or, in most cases, an overlapping mixture. They are generally interesting and usually consequential as well as numerous. A short representative list of the broad issues at hand can reasonably include questions about the very reason for undertaking biotechnology; policy and commitment; technology transfer; safety and risk; who benefits; regulations; labeling; public acceptance; the morality of it all; use of technology in general, particularly that based on living organisms; trade and international implications; sources of capital; process versus product, unexpected consequences; evaluation of outcomes; and fear of the new. More specific issues are those of: cloning; stem cells; bioterrorism; globalization; altered landscapes; new food; biodiversity; genetic privacy; reducing life to genes; rights of animals; rights of plants; control over nature; genetic transference; ownership of germplasm; and xenotransplantation.

While this process—combining stages, participants, and issues—is complicated, the key point is simple: for effective, thoughtful, and appropriate biotechnology development, in any sector, this process and its attendant imperatives must always be understood and always addressed. The reason is clear. For movement along the continuum to be successful and acceptable, a sector—such as forestry—or even a single company must gain or involve all participants, must move through all steps, and must address all appropriate issues.

Lack of required resources and participants at any stage can slow or even stop the process. Without, for instance, trained researchers, or risk-taking companies, or accepting users, technology development is less likely to come about. Failure to address key issues or challenges at any stage can also slow or even stop the process, lessening acceptance as well as economic and societal gain. Here are two easy examples: First, insufficient funding for science at the beginning of the process can truncate a vital movement. Is funding for biotechnology in trees sufficient to ensure good research and good analysis of outcomes? Second, insufficient preparation for public response can curtail the final stage of the process. Was sufficient attention paid early to the issues of food and agricultural biotechnology? Are we preparing early and thoughtfully enough for the ecological, societal, and policy issues to inevitably accompany forest biotechnology?

The reality and implications of the process of technology development are increasingly apparent for the forestry endeavor. Development and exploration of biotechnology make the forestry endeavor now more a technology-directed enterprise than one shaped by its traditional approach and slower-moving results. Traditionally and historically not technology intensive, the forestry endeavor has brought biotechnology to the challenges of this process and of its issues.

Understanding the process of technology development is thus increasingly required for participants in forest biotechnology. The trees of technology are not—in genesis, development, and attendant issues—exactly like the trees of tradition. Reflecting the complicated process from which they spring, they are also more difficult to bring about.

The Context of Technology Development

The process does not take place in a void. Technologies do develop within the life, culture, and values of a society . . . within the *zeitgeist,* as the Germans so nicely characterize this combination of time and spirit. This surrounding context is shaped by history, tradition, relation, values, and expectations, of individuals as well as of society. This cultural and societal context directly or indirectly affects our approach to technology development and, simultaneously if not always clearly, our responses to it. This context shapes research and product priorities, attitudes to risk taking, polices and issues, public and institutional responses, and funding decisions.

Thoughtful awareness of this context, and realistic attention to it, is required for effective, long-term biotechnology development and use. Trees in particular demand such awareness and attention, for our responses to trees are strongly shaped by intricate cultural, personal, visual, and historical factors.

The Imperative of Biotechnology Development

Because shaped by issues and positioned fully within society, biotechnology development thus requires attention—from the beginning of the process and continually—to science, industry, and society in probably roughly equal measure.

No earlier technology has from its onset so required this imperative; none, certainly, has yielded comparable deliberate attention in all three areas simultaneously. Such attention is as much societal responsibility as necessary strategy. Experience reveals that we have too often addressed the ethical and societal implications of technology too late, at the end of the process, as a last thought if not as an after-thought. Sometimes this has been done with admirable intentions, and sometimes more to induce public acceptance.

We must do better with biotechnology, giving attention as appropriate to numerous, difficult, and often very new issues at all points along the continuum of technology development. Identifying, understanding, and addressing different issues at different stags is enormously challenging. Our intentions are good; the community working for biotechnology has proven remarkably aware of its full societal responsibilities. However, practical realities often make difficult our attention to the issues at hand. First, participants vary greatly along the continuum, in their tasks, vantage points, expectations, and values. Second, few participants are appropriately trained, particularly in ethical evaluations. Third, stages and results are usually separated by time, place, and participants. Results or implications later in the process cannot be easily anticipated or controlled in earlier stages. Finally—and perhaps most important in general as well as specifically in relation to forest biotechnology—there is worldwide no common imperative to identify and address all of some of the issues. Worldwide, in fact, we see substantial differences in underlying values, in issues judged important, in ethical frameworks, and in commitment to measured public discourse.

The imperative to effectively, realistically, and credibly anticipate and address the issues of biotechnology is enormous and cannot be questioned. Doing so is neither academic nor a luxury, but is instead the sine qua non of movement from science to public. Analysis and resolution of key issues will be required in some countries if certain research and applications are to move forward. It is quite possible that certain products and applications will be philosophically vetted, rather than more traditionally evaluated largely in terms of feasibility and safety. It is, moreover, possible that certain outcomes, results, or applications will ultimately not be developed, acceptable, or used.

Such considerations will apply, to as yet undetermined degrees, to forest biotechnology, as to food biotechnology, use of stem cells, and human cloning. Accordingly, the imperative to thoughtfully prepare for the issues at hand is strong in particular for all persons and institutions applying new biological science to trees and forests.

THINKING ABOUT TREES

We probably know more about trees than about the unfolding process of biotechnology development.

Trees are profoundly important. They are requisite for life on this planet, key to environment and ecology. They are, and always have been, requisite for civilization, key to human and societal development. They create one of the world's largest and most important economic sectors. They have extraordinarily wide mythic, symbolic, religious, and historical resonance.

Trees have greater impact on culture and consciousness than any other crop or plant. As noted earlier, most people give an intrinsic moral value as well as actual value to trees. Behaviors as well as policy reflect our value-based responses to trees worldwide. Human responses to threats or loss are passionate, emotional, and often shaped by barely conscious imperatives. Forests are preserved by policy in richer or more enlightened countries. Protecting the landscape, in which trees are key, has a moral imperative in a growing number of places.

It is therefore difficult to imagine a more societally challenging global issue than genetic engineering of forest trees.

REPRESENTATIVE FOREST BIOTECHNOLOGY ISSUES

This challenge is understandable. Merging the process of biotechnology development with trees and forests worldwide will yield a rich mixture of questions, implications, and issues—as much societal and ethical as scientific or economic. Science and research, regulations and risk analysis, industrial and societal priorities, environment and ecology, must all be brought to the endeavor, and somehow shaped to safe, appropriate, and acceptable ends.

Forest biotechnology is barely explored, largely just beginning its movement along the continuum from research and science to applications and society. As a result, issues, questions, and implications can be better identified and addressed early; the varied participants can, and should, be brought early to the requirement doing so. Doing so will be demanding, for the intrinsic uncertainties of this new technology in general are further affected by the compelling importance of trees to our consciousness and our planet.

The environmental, societal, policy, and ethical questions arising from forest biotechnology will be consequential. Each is complicated and not easily addressed, combining scientific, industry, and public imperatives. A few can be listed as representative; there are more.

- *Concerning the initial technological imperative:* Why undertake forest biotechnology at all?
- *Concerning a more realistic imperative:* How can forest biotechnology be thoughtfully developed and appropriately applied? How can careful attention to questions and issues at all stages be assured?
- *Concerning the derived benefit:* Who will predominantly benefit from forest biotechnology? Will different benefits be gained by different parties, in a reasonable balance?
- *Concerning the inevitable tension between perceived benefits and perceived liabilities:* The ambiguity often implicit in ethical decision-making about technology might prove particularly vexing in forest biotechnology. How is a determination made between (a) the undisputed need to grow more trees on less land and (b) possible displeasure and risks attendant to widespread plantations of transgenic trees?
    - The environmental and economic value of trees altered to have less lignin content *and* possible related stresses and outcomes to trees so altered.
    - The need to grow altered trees efficiently in controlled settings *and* the diminishment or loss of some forests as rich ecological environments.
    - The imperative that transgenic trees do not flower or reproduce (for improved productivity or to prevent genetic transference) *and* the ecological benefits of flowering to the environmental and to other organisms.
- *Concerning the human imperative to work for improvement and survival:* In the face of varied undisputed factors (including land limitations and the ever-present need for wood products), is it unethical not to develop and apply forest biotechnology?
- *Concerning the state of trees:* Largely non-altered, the wildness of trees is remarkable, contrasting with centuries of deliberate alteration of other key species, and conveys a large part of their appeal. It also suggests possibly easier genetic transference be-

tween altered and non-altered stands.

- *Concerning the long life and large presence of trees:* How can potential environmental outcomes be anticipated over many years? How might genetic alternations prove unstable or yield unexpected changes over time?
- *Concerning the tree versus the forest:* How do quantity and clustering matter? Are fewer genetically altered trees (here and there, in parks and orchards, in your back garden) more acceptable than large numbers neatly arrayed? Why?
- *Concerning the type of altered tree:* Are apple trees immune to fungus in northern Europe, or regained American elms, more acceptable than pines altered for quicker timber production? Why?
- *Concerning managed tree plantations:* Intensively managed plantations increase steadily worldwide, with good reasons, but often yield responses different than for other large crop plantings. Will forest biotechnology plantations yield even more acute responses?
- *Concerning variable regulatory and policy frameworks worldwide:* Countries vary in their attention to testing and trials, as well as their attention to ethical guidelines, the environment, and public discussion. Forest biotechnology will likely be early applied in countries with less strong imperatives or experience in these areas.
- *Concerning the status of countries involved in forest biotechnology:* Will forest biotechnology gain germplasm and economic benefits for a few nations, at the expense of those less sophisticated or less economically developed?
- *Concerning the landscape:* Honoring and preserving the landscape is a moral imperative. So is improving it, but agreement is less clear on acceptable means. Do genetically altered trees violate this imperative, in large or small numbers? Other alternations to trees do not seem to do so.
- *Concerning the many, varied, and complicated environmental implications to which attention must be paid:* Environmental and ecological questions are inherently as much ethical as scientific, and should be judged as such. Avoidable harm to the environment and living organisms is a prime moral failing.
- *Concerning the ethical slippery slope:* Threatened or diminished tree species can realistically be regained in time through biotechnology. Does this prepare somehow for regaining other, non-crop, species?
- *Concerning dialogue and engagement:* Ethical standards are needed for development and application, but also for discourse and opposition. Parties reflexively polar (on either side) can probably be discounted.
- *Concerning the forests on which life depends:* What do we expect of our forests? How do we define—or refine—the natures, outcomes, and uses of a forest?
- *Concerning the passion that trees so understandably induce:* How can firmly held often inchoate passion about "natural" trees exist with a realistic recognition that they are necessarily, in some cases, resources to be altered? How can understandable emotion find balance with practical technology?

Persons and places attentive to trees—and forest biotechnology—worldwide must begin to address such questions. How can this be effectively done? What framework or resources can assist?

THE INSTITUTE OF FOREST BIOTECHNOLOGY

Answers, strategies, and assistance will be required for many years. Over coming decades, without question, forest biotechnology worldwide will mix science, industry, society, technological process, participants different in tasks and agenda, and layered issues. This complexity must be granted, discussed, and somehow addressed by the widely divergent parties attentive to forest biotechnology.

The task is demanding and consequential. Remarkably, no entity had until recently been established to address the task and the challenges. This void was seen as surprising by persons attentive to forest biotechnology, and also as a liability. The absence of a strong central voice for forest biotechnology lessened the likelihood that policy and issues worldwide will be addressed with appropriate strengthen, credibility, and thoughtfulness.

Responding to this absence, a diverse committee of over 25 persons was brought together by the North Carolina Biotechnology Center, catalyzed by a reasonable premise: forest biotechnology could be assisted from the onset by an organization directed to partnership, the issues at hand, and multiple vantage points. The group—representing research, policy, academic, public, and corporate interests— worked over an 18-month period, from 1999 until early 2001. Merging imagination, long-term vision, and common sense, the group crafted the philosophy, approach, and governance of a new entity: The Institute of Forest Biotechnology. The mission of the newly-established Institute is bold in nature and large in intent: To work for societal, ecological, and economic benefits from appropriate uses of biotechnology in forestry worldwide.

The North Carolina Biotechnology Center has committed initial funding of over $300,000 to the Institute, which will be housed administratively at the Center until resources are available for an independent site. Additional funding is sought, and over time must come in appropriate balance from project, industry, government, and foundation sources. The Institute's first employee, Ms. Susan McCord, has initiated activities.

The *sensibility and approach, emphases, governance,* and *expected key initial activities* of the Institute are outlined below.

Sensibility and Approach

The challenges of forest biotechnology demand imagination, non-standard problem-solving, and innovative partnerships. Accordingly, the Institute will, through activities, governance, and philosophy,

- Serve varied parties attentive to forest biotechnology, within the process and within the larger societal environment, as convener, problem-solver, common ground, and partner.
- Assist existing organizations and activities rather than unnecessarily duplicate efforts.
- Work for activities and decision-making informed and balanced by diverse voices.

Emphases

The Institute will direct attention and activities to three main areas. In *Science and Research*, the Institute will

- Identify key topics for societal, ecological, and genetic research.
- Work for partnerships and funding.

In the area of *Policy* the Institute will

- Identify areas in which forestry, regulatory, technology, or public policy is required.
- Coalesce partnerships and projects.

Responding to *Societal Imperatives*, the Institute will

- Identify key areas of societal, environmental, policy, and ethical issues.
- Develop educational materials, projects, and multi-party meetings.

Governance

Twenty board members will manifest the imperative for varied voices, representing three main groups in roughly equal balance: public interest and non-governmental, academic and governmental, and industry and industry-related. The first 10 board members have been determined: Christine Dean, Weyerhaeuser; Robert Friedman, the H. John Heinz III Center for Science, Economics, and the Environment; Robert Kellison; Lori Knowles, the Hastings Center; Dennis LeMaster, Purdue University; Alan Lucier, National Council for Air and Stream Improvement; John Pait, The Timber Company; Ronald Sederoff, North Carolina State University; Ben Sutton, CellFor; and myself.

Expected Key Initial Activities, 2001–2002

Administrative goals are to

- Gain an exceptional Executive Director
- Move to full 20-member board
- Work for short- and long-term funding.

Communicational activities will initially

- Inform parties worldwide about the Institute
- Gain responses about activities and approach.

Addressing ecological and ethical issues, the Institute plans to

- Commission a scientifically based study of the ecological risks associated with forest biotechnology
- Sponsor a workshop bringing together diverse parties to shape and address these issues.

The Heritage Trees Program, the Institute's first program, has a direct premise: the tools of biotechnology can be used to regain or strengthen threatened or diminished species, yielding the best possible combination of scientific, ecological, and societal outcomes. The Program will

- Commission a report to identify key species and what tools of molecular biology can be appropriately brought to bear upon them.
- Sponsor a workshop to coalesce partnerships and to focus efforts of varied groups.
- Develop a peer-reviewed grants program to help fund targeted research.

Information and Technology Transfer activities will

- Develop a short publication introducing forest biotechnology.
- Develop the Institute as a site for information and resources on forest biotechnology.
- Respond to initial requests from institutions and industry for project assistance.

Development of the Institute of Forest Biotechnology is enormously demanding and challenging . . . but also valuable in due proportion to the challenges and issues to be raised in coming decades by the application of biotechnology to trees and forests.

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Will the Marketplace See the Sustainable Forest for the Transgenic Trees?

Don S. Doering

Abstract

A public or privately financed market for genetically engineered trees depends upon how the technology is applied, who participates in the decisions of commercialization, and society's general acceptance of the release of genetically engineered organisms into the environment. The international debacle of the introduction of genetically engineered food and fiber crops provides valuable lessons to the nascent tree biotechnology industry that products must have broad social utility, be designed for environmental safety, and be tested for ecological impacts. The introduction of genetically engineered trees can occur via an appropriate regulatory framework and a collaborative effort of the public and private sector as well as stakeholders from civil society. Meeting the future global needs for fresh water, biodiversity, materials, energy, habit, and paper will require keeping sight of the sustainable forestry goals beyond the transgenic trees.

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Forests and tree plantations can sustainably provide all the necessary goods and services—from timber to protected habitat—that the world wants. Today we are far from that sustainable ideal. The genetic engineering of trees has the potential to contribute to both sustainable and unsustainable forestry practices. That contribution of genetically engineered trees depends on the private and public use of the technology and how economic markets develop for wild and domesticated trees. Will that marketplace develop and who will shape its path?

This essay is based on the assumption that genetically engineered trees will be commercialized, but the timing and trajectory of commercial introduction are far from certain. Will a market develop in some countries, while intense societal opposition closes markets in other regions, as has been the case for genetically engineering food crops? Can we learn from the experience with other genetically modified organisms to improve the chances that public and private genetic engineering of trees will safely and fairly serve the needs of society? The view presented here, based on observation of crop biotechnology, is that there may be conditions under which transgenic trees reach the marketplace. But the needed pre-conditions of stakeholder engagement, increasing the social utility of products, novel partnerships, and design-for-environment call for a new approach to commercial genetic engineering of plants and a break with the example of first-generation genetically engineered crops.

GM Trees: How and When, Not If

Genetically engineered trees are in the environment. In hundreds of experimental field trials of dozens of species and in dozens of countries, private and public sector scientists are conducting research on transgenic trees. None of these trials are pre-commercialization, however many may be viewed as commercial prototypes. The cautious but obvious interest of the forest industry and interest among academic scientists in genetically engineered trees is reminiscent of the early moments of agricultural biotechnology. As described below, a set of forces lend an air of inevitability to commercial introduction of genetically engineered trees.

Even as genetically engineered trees are intriguing, it is hard to imagine that a forest industry executive or tree biotechnologist would want to see product introduction of trees follow the example of GE food crops. At first glance, introduction of herbicide resistant and pesticidal crops is a story of fantastically fast technology adoption and market penetration. Only five years after their introduction, almost three-quarters of U.S. cotton, over half of U.S. soybean and a fifth of the U.S. corn crop is planted in GE varieties (Carpenter and Gianessi 2001). With another look, introduction of GE food crops is a product introduction nightmare. Agricultural biotechnology CEOs have been fired or replaced, corporate reputations have been shaken, billions of dollars of shareholder value has been lost, and ag-biotech divisions of large companies have been swapped, closed, and expelled from their parent companies. The societal unity in Europe in rejection of biotechnology crops has slammed closed valuable grain markets and 'frankenfoods' have become an icon of the global anti-corporate and anti-globalization movements. Some of the same companies involved in food crop biotechnology are involved in GE trees, many field trials are testing the same traits of glyphosate tolerance and *Bacillus thuringiensis* (Bt) endotoxin expression, and the aspirations for tree biotechnology by its proponents share many similarities with the aims of crop biotechnologists. As we contemplate increased corporate and public investment in tree biotechnology, it is fair to wonder how will society benefit and how many corporate casualties will there be along the way?

LISTENING TO THE LORAX: CREATING A 21ST CENTURY MARKET

The Lorax is a clear and compelling story of unsustainable forest management and unsustainable business strategy (Seuss 1971). The book presents a 20th-century view that a market is created by product performance, supply, and demand. In the classic children's story by Dr. Seuss, the Once-ler uses the fiber of the Truffula Tree (species unknown) to knit thneeds, a multi-purpose textile that is "a-fine-something-that-all-people-need." The demand is immediate, voracious, and is served by the Once-ler's innovation that automates thneed production and Truffala harvesting—over the repeated and furious objections of the Lorax. The Lorax is himself a forest resident and the spokesperson for other Truffula ecosystem stakeholders such as the Bar-ba-loots, Swomee Swans, and Humming Fish. As the thneed industry and tree harvesting degrade the basis of the ecosystem, the native species migrate, the resource collapses, and the thneed business collapses. The Once-ler is left in financial ruin and—too late—becomes an advocate of ecosystem restoration.

Were Dr. Seuss to invent this story today, he might incorporate powerful features of the 21st century marketplace. This is still a time of powerful multi-national corporations in which supply and the openness of markets are strongly influenced by corporate intentions and political influence; technologies are still pushed to the marketplace. Product performance now includes the consumer demand, regulations for product lifecycle stewardship, recycling, and environmentally friendly design. The ability to sell to society is now governed by demand and the societally granted license-to-operate. As is so richly illustrated by European rejection of America's genetically engineered crops, stakeholders exclusive of customers and shareholders now have the power to close global markets through protest, political power, and boycott. Corporations (including some of the largest timber companies and largest wood-buyers) have been forced to change business practice and strategy because of civil society activism. Social license-to-operate, societal acceptance, stakeholder engagement, and corporate social responsibility are now central strategic issues of business leadership and not just public relations functions. In today's update of *The Lorax,* the Lorax would be supported by outside activists in his thneed opposition, bar-ba-loots would be found chained to trees and to thneed shop shelves, legislation would protect the Swomee Swans, and perhaps the story would have a different outcome.

THEMES OF THE SOCIAL CONTROVERSIES OF CROP BIOTECHNOLOGY

Genetically engineered crops unified many social movements that had never been so united and so armed with potent symbols such as baby food, monarch butterflies, and the small-scale farmer. A common cause was found that united individuals and NGOs with interests in food safety and consumer choice, farmers' rights and property rights, spirituality in a technological world, economic justice and global trade, corporate influence and economic justice, hunger and the environment.[1] Recognizing this confluence of interests is not to deny their validity but it helps to see underlying themes that merit deep consideration by a nascent forest biotechnology industry: individual choice, product safety, social utility, transparency, and ethics.

Genetic modification itself is controversial yet we have examples that society weighs its risks and controversies against benefits. The genetic engineering of microbes to produce vital medical therapeutics such as insulin or erythropoietin is acceptable because the organisms are under high containment and unable to replicate in the environment, the product has a clear utility in saving lives, and the medial consumer has information and choice.

The first products of the biotechnology industry were seen (and still are seen by many) as being potentially unsafe for humans, animals, and the environment. The utility of the products to the consumer and even to the farmer are questioned. Not only is the transparency of companies under fire, but so has been the pro-biotechnology stance of the U.S. and European governments and the lack of transparency in the regulatory process for GE crop approvals. But perhaps of greatest societal distaste to opponents of biotechnology is the lack of personal choice in choosing foods derived from genetically engineered commodities, coupled with the perceived unethical and opaque actions of the biotech companies in seemingly imposing the products upon the market.

TRUST

The benefits of transparency, respected ethics, and the support of social values are captured in the word *trust*. The ag-biotechnology companies, and by association many scientists who worked with those companies, have largely lost the trust of the politically active public, particularly the 'anti-biotech' activist organizations. The loss of trust has many origins, some of which hold lessons for commercialization of GE trees. The public's experience with automotive, tobacco, pharmaceutical, chemical, and oil companies has created suspicion when large and apparently powerful companies claim to act in the public good and make loud protestations of public safety and benefit. The logging and timber products industry has similar reputational liabilities for its poor past environmental record and political influence; images of clearcuts on public lands and protesters blocking logging trucks have been potent symbols throughout the last 30 years of the environmental movement. A union of the timber industry and the plant biotechnology industry comes poorly armed to a battle based upon public trust, and is a dream marriage to an anti-corporate activist (Lenzner and Kellner 2000, Sampson and Lohmann 2000).

The agricultural biotechnology industry used, and still uses, the promised benefit of biotechnology for sustainable food supply to earn its social license to operate. In doing so, they may have picked the wrong arena for taking on opposition interests. First-generation biotechnology products did not address causes of food insecurity and were not designed to be grown in climates or designed for agricultural systems where there is food insecurity. The arena of food security and sustainable agriculture put the industry in debates with opponents with superior knowledge of global food needs and with harsh critiques of industrialized agriculture.[2] The companies' relative financial investments in 'public good' projects vs. industrial agriculture projects are in no way proportional to their treatment in the industry's public relations material. Such dissonance

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[1] *See for example: The Genetically Engineered Food Alert (www.gefoodalert.org), The Organic Consumer Association (www.purefood.org) and The Five Year Freeze (www.fiveyearfreeze.org).*

[2] *It is fair to note that many biotechnology opponents continue to make a similar strategy mistake in arguing against biotechnology on scientific grounds when actually their objections are rooted in much more complex social and economic issues. As the scientific community inexorably and effectively addresses those issues, the chance for valuable and productive societal debate is missed.*

between message, image, and action fuels distrust.

Forest biotechnology will not save the world forests in the coming decades any more than crop biotechnology will solve problems of food insecurity. Technology is only a small component to solve problems rooted in long historical economic and political inequity, environmental mismanagement, and traditional harvest practices. There has also been little or no detailed analysis today to say that genetically engineered trees might relieve pressures on threatened biodiverse forests or might significantly impact pulp and paper supply in the regions of highest future demand.

The lesson for business is to transparently test, quantify, and communicate the economic benefit of tree biotechnology to themselves and to society. The typical consumer understands the desire of businesses to grow, to reduce costs and to eliminate environmental liabilities. Genetically engineered tree plantations in regulated and industrialized markets may well improve corporate profitability and lower a company's net environmental impacts. "We're doing this for our business" will resonate more truly with a skeptical public than will claims that massive investments in new industrial technologies are motivated for the local public good or are intended to directly save distant threatened forests. A transgenic pine in Georgia will no more save the forests of Indonesia than will an improved soybean grown in Iowa benefit the food-insecure peoples of Africa and Asia. Business messages are more effective when true and simple, rather than simplistic.

MAXIMIZE SOCIAL UTILITY

Sustainable business is business that raises its social utility by creating environmental and social value in addition to economic value, while not depleting resources. Good environmental performance in the past meant doing "less harm." Today's stakeholder demands performance beyond regulatory compliance and favors companies and products that do "more good" rather than less harm. Many have observed that there would have been societal acceptance of biotechnology if only the first products had yielded direct consumer benefit such as better-tasting, more convenient, safer, more nutritious, or cheaper foods. The same will be true of forest products. An often associated observation is that the agricultural biotechnology industry has asked the public to bear unknown risks of genetic engineering with no perceived direct benefits.

A public invited to live next to genetically engineered forests or orchards will ask "are we getting wood or paper that is better, stronger, longer-lasting, more appealing or cheaper? Or "are we getting fruit that is better-tasting, longer-lasting, more nutritious, or cheaper?" Considering the lack of differentiation and low cost among so many timber and paper products, the products of genetically engineered trees may not deliver these kinds of direct consumer benefits. With farm costs (plantations in this case) as a small component of retail costs combined with the high costs of regulatory approval and compliance, it seems equally unlikely that products of genetically engineered trees will be cheaper. So how can forest biotechnology create social benefit for those that may bear unknown environmental impacts?

HIGH IMPACT PRIVATE FOREST BIOTECHNOLOGY

Among the traits and benefits under consideration for forest biotechnology that may have the greatest social utility are the reduced-lignin designs that may lower the chemical, water and energy use, and pollution created by the pulp and paper industry. Though the cost savings may not reach far down the value chain, the benefit will occur at the site of milling. The communities at or near the plantations and the paper mills may receive a net environmental benefit of cleaner water and air in their communities. These properties may even allow branding of an otherwise undifferentiated product. But there is a catch. Selling cleaner processes involves admitting current environmental liabilities and dirty processes. How much of a paper company's resource base has to be from reduced-lignin trees to make a measurable and transparent environmental impact and to outweigh subjecting all its production to scrutiny? As air and water regulations and energy costs put increasing pressure on the industry, the day may come surprisingly soon.

A second intriguing trait for social utility is fast growth. In this case the goal would be to develop a fast-growing pulpwood or hardwood with a short enough rotation time to change the economics of logging in biodiverse frontier or secondary forests. Like in the lignin example, benefits would need to be regional, if not local. A company may convince the public that its fast growing GE tree plantation removes its need to log on public and private lands. If that claim was proved by selling or giving private forest lands to the state for public use, it would be that much more convincing. It will be hard for a forest biotechnology industry to justify genetically engineered trees in places such as New Zealand, Canada, Europe, or the United States on claims that it relieves pressure in Russia, Indonesia, the Amazon, or Gabon. Agricultural biotechnology has revealed the different cost-benefit equations in different parts of the world. A fast-growing tree plantation in Asia that saves adjacent forests and meets local pulp demands is a different proposition. Environmental safety is most like to be met by multiple, benign mechanisms for tree sterility and plantations managed for biodiversity and ecosystem services. In either the case of reduced-lignin or fast-growth, a private company will have to meet the highest standards of environmental safety, ethics, and transparency to win the public trust.

HIGH IMPACT PUBLIC FOREST BIOTECHNOLOGY

A market for tree biotechnology need not be an economic market in the strict sense, but might be developed through the public investment in tree biotechnology. What if publicly funded agricultural biotechnology had preceded the private sector's rush to market? It is easy to imagine a public more receptive and a market more open to genetic engineering if the first we heard of genetically engineered crops was Vitamin A-enhanced rice, a sweet potato to feed Central America's hungry, or a high-protein cassava that grew in the depleted soils of East Africa.

This "public-first" scenario is still possible with tree biotechnology, though it will require large investment and careful choice of target species and preferred traits. The first public priority may be rapid reforestation of abandoned and degraded agricultural lands to create measurable benefits of soil stabilization, watershed protection, habitat restoration, and timber production. Fast-growing plantation trees designed for tropical zones might also be used to create plantation buffers around threatened tropical forests to supply pulp, timber, fuel, and forest products to local communities. Fast-growing fuel woods that grow on marginal soils might also help protect forest frontiers, raise living standards, and support economic development.

Another possible development that would facilitate public acceptance of genetically engineered trees would be specific disease resistance that saves a tree of high environmental, economic, or symbolic value. In America, genetic engineering for fungal resistance that would allow the restoration of the American elm and American chestnut to Eastern forests could have a large positive impact on ecosystem restoration and upon the tourism, landscaping, timber and forest-product industries.

There are a wide variety of projects under way in the public research sector on reduced or increased lignin content, increased cellulose content, faster growth, more uniform growth, growth in marginal or arid soils, and other projects. The apparently small investment in these projects and their use of the plantation species of the developed world may not produce the near-term and high-impact "icon" products described above that would shape societal opinion. Other alternatives that seem much more fanciful in their benefit and technical realizations include engineered control of stress response and adaptation to allow adaptation to climate change, production of bio-based fuels, and trees designed for carbon sequestration.

Public sector efforts in tree biotechnology face the same challenge as the application of agricultural biotechnology to global food needs: lack of scientific knowledge of tropical species, lack of scientific and regulatory capacity in developing countries, diversity of species and culture methods, and the concentration of R&D dollars and intellectual property in the private sector. The research agenda today is not driven by a global analysis of needs and the functions of trees and forests. Creating a genetically engineered tree to deliver measurable public benefit would call for tens of millions of dollars in public and private scientific investment that is guided by a deep needs analysis and public participation.

DESIGN FOR THE ENVIRONMENT

An informal mapping performed at WRI of the environmental issues of genetic engineering of food crops sorts issues into those of direct impact, such as human food safety, ecosystem harm, animal safety, loss of genetic diversity, resource depletion, and unknown impacts and the indirect impacts that genetically engineered crops may have on the intensification and spread of industrialized, chemical-intensive monoculture. At least four primary mechanisms may mediate most of the direct environmental threats such as toxin production, gene disruption, weed creation, and genesis of new pathogens. At the root of almost all these potential risks are three core issues: the control of gene expression, the potential of gene transfer, and the intended design of the engineered organism.

Most agricultural molecular biologists don't label themselves as genetic engineers, and the language of engineering and design is not used to describe genetically modified crops. However, these crops are engineered products, and an engineering mindset would serve the industry and society. Engineers have spent the last several decades learning and proving that environmental benefit is best achieved by design, and that approximately 80% of the environmental impact and costs of a product is determined at the point of design (Tischner and Charter 2001). The end-of-pipe solutions of scrubbers, waste treatment, and toxic disposal are far more costly to society, business, and the environment than pollution-prevention at the moment of design. The same is true of genetically engineered crops and the same will be true of genetically engineered trees.

The agricultural biotechnology industry is just coming to appreciate the implications of design and the analogy of front-of-pipe designs to reduce cost and risk. Consider as an example, that the design of Bt corn was simply to achieve gene expression in corn. The accomplished goal of constitutive expression of Bt toxin in all corn tissues, among them the corn pollen, has lead to the high costs of testing on pollen flow, the need for extensive refugia, complex grower contracts and compliance schemes, and the persistent controversy of impacts on non-target lepidopterans such as the monarch butterfly. Another example of design failure is the need to eliminate antibiotic resistance markers and to develop alternative selectable markers. These cases suggest principles for design, such as that (1) the introduced gene should only be specifically released into the environment; and (2) there be no functional open reading frames in transformants, except the gene of interest.

Had such principles guided the priorities of basic and applied research, the risks and benefit of first-generation biotechnology products may have been very different. Tree biotechnologists can adopt the mindset of green product designers and use design principles for environmental safety to drive their product development agenda and to identify frontiers of basic research. The transgenic trees planted to date for research purposes should be recognized as the experiments that they are and should not be confused with product prototypes or with products engineered for the market.

THE IRONY OF INPUT TRAITS

Environmental impacts, commercial benefit, and social acceptance are specific to the engineered trait and to the physical and cultural context of the silvicultural system. This point cannot be over-emphasized; the engineered trait (i.e., the modification and its expression in the plantation context) is the determinant of direct and perceived social utility. The first crop biotechnology products to see large-scale planting all featured "input" traits. The input traits act as production inputs or work in conjunction with production inputs to the agricultural system and their benefits accrue to the supplier of the input and to the farmer; the marketed product has no new functional characteristics.

Only a small volume of crops such as soy, canola, corn (and even cotton for fiber use) are consumed in their pure form, and they are chiefly the low-cost ingredients to value-added food products. Farm-gate prices of most commodities are at historic lows in the United States, and the farmer's share of the consumer dollar spent on grains and vegetables is roughly \$0.04–\$0.07 (National Agricultural Statistics Service 2001). Small improvements in farm productivity or reductions in input and labor costs are imperceptible to the final supermarket customer. The impact of the input traits such as pest and herbicide tolerance have no direct cost benefit to the end consumer of the engineered crops, and it is worth calculating whether any input trait could have a direct consumer price benefit.

For herbicide tolerance, the environmental benefits are the replacement of more toxic herbicides by glyphosate and the adoption of no-till farming methods that save labor, fuel, soil, and water. For the Bt crops, the benefits are reduced dependence upon more toxic pesticides. The input traits of herbicide and pest resistance for food crops delivered little perceived social utility for their claimed impact upon the environment and food safety; the reasons bear lessons for tree biotechnology.

First, the general public is unaware of and may not want to know the quantity and nature of chemicals used on crops in industrial agriculture or of the negative impacts of modern farming. The benefit of "less herbicide" draws attention to the use of chemicals and associates the consumer product with chemical intensive and "non-natural" farming. Although no-till farming is an important advance, complex environmental issues of destructive farming, non-point source water pollution, and soil loss are distant from the decisions about food purchase. The dramatic growth of the organic foods market is largely a testament to fears of the safety of foods and to a lesser degree, environmental concern. The creators of food brands want to associate food with a natural rather than destructive image of farming. Less harm is not as compelling an association as crops that deliver more societal good. Second, the data on the economic and environmental benefit of herbicide resistance in food crops has not been transparently shared by the sponsoring companies and has been publicly questioned by critics of biotechnology.

Third, glyphosate or Bt toxin and the chemicals it replaces are produced and sold by the same set of agrochemical companies and are used by the same customers and are all approved by the same regulatory authorities who also sell, use, and approve the genetically engineered seeds. Drawing too much attention to the chemicals and their relative food and environmental safety (which should be comparable when used within approved limits) might also draw criticism to the agrochemical industry, the regulatory authorities, and the farmers—a no-win situation for everyone. The last reason why herbicide resistance was not marketable to consumers returns to the idea of trust—and that those who promoted the benefits are also those who would profit the most by selling the seed and the herbicide. Balanced against no direct cost benefit and unappreciated indirect benefit are fears of environmental risk and human health risk. "Why should I bear even remote or unknown risk, if others profit and I don't benefit?" demands the concerned consumer.

A similar set of reasons explains why there is no perceived direct consumer benefit to the pest resistant traits. For the Bt toxin crops, the simple description of the crop is that it produces its own insecticide instead of using insecticidal chemicals—drawing attention to the use of chemicals and to the fact that the consumer may be eating a poison, though harmless to humans. The environmental benefits were also not transparently communicated to the customers of foods that contain biotech-derived ingredients, and there were charges from environmental activists of threats to nature and beneficial insects, as well as threats to the purity of organic crops. Drawing consumer attention to the EPA and FDA's findings that either genetically engineered crops or chemical pesticides can be used safely is not a consoling thought to today's consumer. Perhaps another incongruity in communicating the benefit of genetically engineered crops was the resistance of the industry to label consumer products in a consumer society where advantages are so prominently emblazoned on product labels. A citizen logically wonders, "if this is so good for me and the environment, why isn't it advertised on the label?"

To a world that does not perceive trees as crops and perceives forests as symbols of nature, trees that produce bacterial insecticides or are made to be sprayed with chemicals are not likely to be accepted if there are perceived environmental risks. Transgenic trees designed to be herbicide tolerant for the benefit of survival at the seedling stage or long-term plantations of trees expressing Bt toxin irrespective of pest levels seem a poor starting point for the industry. The message to forest biotechnologies should be very clear: commercialize output and social utility traits well before commercializing input traits that might increase chemical use, promote chemical use, or that draw attention to chemical use and the "unnaturalness" of tree farms.

PRESSURES ON THE FOREST INDUSTRY

Discussion of forest biotechnology often starts with "does the world need transgenic trees?" This is a very important question and may be an important guide for public sector research and development. More immediately, the question might be, "does industry want transgenic trees?" Agricultural biotechnology has shown that when there is a powerful economic motivation for industry, the genetically engineered products will be developed. The strong financial push and pull on Monsanto from their huge investments in seed companies and rising valuation on Wall Street was a powerful accelerator for GM crop introduction and created a competitive environment that demanded a similar response from Monsanto's agrochemical rivals, including Dow, DuPont, Aventis, and Novartis (now Syngenta).

A crude snapshot of the forest product industry (timber, pulp, and paper) shows an industry under regulatory pressure, rising competition from global competitors and an industry that is striving for modernization, value-added products, and an improved reputation. The public pressure from activist organizations on both ends of the value chain, from the logging companies, to paper mills, to the do-it-yourself chains has been great. The result of that pressure is unprecedented demand for products from certified forests and a directive for the industry to transform itself from one of the last extractive industries to a sustainable industry based on renewable resources.

This creates a conflicted context for forest biotechnology. The vision of proprietary and advanced technology and the seductive visions of genetically engineered super-trees must be alluring to leaders of an industry of bulldozers, chain saws and pulp mills. Moving out of contested forests and into privately owned plantations must also be attractive. At the same time, product development costs and regulatory costs and the visions of anti-biotechnology protesters destroying test plots of trees and attacking company CEOs must make the same business leaders distinctly queasy.

NEW CAPABILITIES AND CULTURE

The movement into genetically engineered trees also calls for a significant cultural and technical change in the industry. For the agrochemical/ pharmaceutical giants, the technology and regulatory processes of genetic engineering were not entirely new, and played to their competitive strengths. The molecular biology, ecological testing, compliance issues, intellectual property strategy, and regulatory processes to commercialize a transgenic tree are not part of the traditional and current capabilities of the forest product industry.

The first transgenic tree plantations will have measures for biological and physical containment, intensive ecological monitoring protocols, and fences or barriers for economic and physical protection. The long-term impacts of transgenic plants are unknown and thus the potential long-term liabilities are only subject to speculation. One thing is certain: that a strategy, culture, and physical method for long-term product stewardship is particularly important for transgenic trees. All these features will raise costs and demand skilled labor and new management methods. Thus, a transgenic tree needs a new public orientation to trees as crops, new science, new regulatory systems, and new management practices in the industry for product development, product stewardship, and plantation management. Each of these changes lowers the probability that the companies at the front of the learning curve will profitably execute product introduction.

The Role of Scientists

Besides the external pressures on the industry and the need for new capabilities, the scientific community itself facilitates and confounds good decision-making by the industry. Biotechnology has been science-driven, as new discoveries seek applications and economic value. In areas of biology less funded than human biomedicine, genetic engineering raises the possibility of increased funding, scientific interest, and the potential for riches to scientists, investors, and research institutions from patents and new biotechnology companies (Smith et al. 1999). For scientists who have spent lifetimes studying forest and tree biology, genetic engineering is a powerful tool to unlock scientific mysteries. Enthusiasm for the science and technology is real and understandable in the world of science. Whether the motivation of scientists is the purest interest in discovery, a genuine hope for sustainable technologies, or the desire for recognition and fund-

Table 1. The possible pitfalls of forest biotech?

- Lack of expertise that bridges sectoral gaps and interdisciplinary gaps
- Lack of analysis of global or local needs
- Seeking public trust upon altruistic claims of distant environmental benefits
- Failure to engage stakeholders in product and field trial design
- Failure to create public-private partnerships
- Commercial pressure to go to market too early
- Regulatory costs create pressures for unethical practices
- Imitation of agricultural products; the lure of easy input traits
- Science-driven choices rather than market-pulled
- Over-valuation of patents
- Long-term liability and stewardship issues

ing, there is a powerful confluence of reasons to be excited and to promote genetic engineering of trees.

The basic scientists at the forefront of exploring genetic engineering of trees are the scientists sought as advisors and collaborators for the companies exploring the possible commercialization of genetically engineered trees. This was also the case for crop biotechnology; so why was industry totally unprepared to address and resolve so many environmental and social issues? The reasons are the belief system of "sound science" and the absence of other scientific and social science viewpoints. The molecular biologists and the corporate strategists thought that the other party had a handle on the potential risks of the products. Missing from the implementation were ecologists and representatives of civil society that might have guided product design and introduction. Today, the agricultural biotechnology companies have put in place high-level stakeholder advisory boards from diverse societal arenas, though it is too early tell how those boards are impacting company action.[3]

One still hears the mantra of 'sound science' repeated in debates on biotechnology and the implication that if only the public understood the science, the products of biotechnology would be embraced. Sound science does not shape the marketplace and is low on the list of the basis of consumer choice. Fears, desires, and price shape consumer acceptance, and this is obvious from the cars we drive, vitamins we take, clothes we wear, foods we eat, and the risks we bear for pleasure and convenience. The priorities for genetically engineered trees should not be guided solely by 'sound science' and scientists. The pressures on industry and the motivations of scientists in regulated and in less-regulated emerging economies create a force for the development of transgenic trees, and scientists can be inspired to serve society and be held accountable if other sectors of society become engaged in this issue.

THE ROLE OF INTELLECTUAL PROPERTY

Intellectual property often assumes a central role in the strategies for the development of genetically engineered products. Patents are credited with being the foundation of the pharmaceutical industry and with creating the conditions for the birth of the biotechnology industry; the patent race accompanying the human genome efforts reflects their continued importance to the industry (Regaldo 2000). Intellectual property has also been one of the most contentious issues in the opposition to biotechnology for the validity of patenting life forms, the use of patents for economic control and competitive advantage, and the patenting of species considered to be in the public domain and natural patrimony of developed countries. Although the value of patents is a common assumption, there is also an analytic literature to suggest that patents are often overvalued, do not create strong competitive barriers, and have lower economic value and strategic utility than is often assumed (Mazzoleni and Nelson 1998; Cohen et al. 2000).

A tree biotechnology initiative will have to deal with the large suite of patents on molecular methods and genes likely to be used to create a transgenic tree. But should tree technologists seek to patent engineered species and their underlying technology? If genetically engineered trees are owned by the same companies that will grow and process the trees, do they need the same protection as seeds for crops that may pass through a complex value chain? Are the costs of the patents in direct terms and in potential societal opposition justified when weighed against the extremely long life-cycle of trees, the ease with which ownership may be established and protected, the rapid development of new technologies, and other means

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[3] *The author is a member of Monsanto's Biotechnology Advisory Council.*

to protect property? The case for patenting trees is not obvious, merits analysis, and may be a weak and incorrect strategic assumption.

COMPARISON OF FOREST VS. AG-BIOTECH INDUSTRIES

This essay has explored the analogies between genetically engineered trees and crops and the system that has produced commercial products with a central thesis that the forest industry can learn a great deal from crop biotechnology's failings. There are, however, important differences between the two industries, and some that may help prevent repetition of the same mistakes (Table 2). First is that the technologists are the customers themselves. The companies sponsoring research and development in genetically engineered trees are forest landowners and timber product companies; the understanding of industry needs that guides R&D originates in the industry itself. Though it is not yet clear, there seems to be no explicit interest in the export and sale of transgenic seedlings, though the high cost of product development will probably create the pressure for exactly such a value capture strategy. The molecular biologists involved in engineering trees were first trained as tree and forest biologists, and may be more likely to consider the wild and managed biological context and complex forest system than their crop science colleagues.

Table 2. Key differences of fiber vs. food biotechnology industries.

- The leading technologists are the customers of the product.
- No agri-chemical industry equivalent; less financial pressure.
- Limited intention of exporting and selling genetic stocks.
- Understanding of needs originates in the industry.
- The scientists are tree- and forest biologists with systems approaches.
- Industry is already undergoing change.
- Ecological damage of the forest industry is recognized.
- Transition to plantations is underway.
- Long timeframes in tree science and business.
- Naturalness is not a quality of paper and timber.
- Fiber system is simpler and more public than the food system.
- Fiber is less contentious than food.
- Forests and trees have high symbolic value.

The forest industry is already undergoing significant change and modernization, and genetic engineering, rather than catalyzing disruptive change—as it did for the old chemical and drug companies—exists in the context of other changes toward greater environmental and social responsibility. The negative ecological impacts of the timber and pulp industry are already recognized; they make up a powerful story in the public mind. It may take a while for people to see trees as crops, but the acceptance of plantations is underway. The tree industry does not have the legacy of infrastructure and planting practices as crops, and there may be some chance of a biodiverse and 'eco-silvicultural' practice developing with lower barriers, rather than changing agriculture to a different model. A transgenic tree plantation may not seem much more unnatural than just the plantation itself, and the view of genetically engineered trees may be different if it occurs as part of a gradual and environmentally responsible transition to tree plantations.

The forest product industry does not have the benign image of farming; it may be possible to sell plantations and engineered trees for doing "less harm" than logging in natural or public forests. 'Naturalness' is not a consumer value of most timber and forest products; we do not seek a natural quality to our lumber or copy paper as we do to a piece of corn, a vegetable, or fruit. This is shown by the relative objections to genetically engineered cotton in contrast to genetically engineered corn or genetically engineered wheat. Cotton is also the one crop where there is the clearest data that shows lowered use of harmful chemicals on the industrial cotton crop (Carpenter and Gianessi 2001). An average consumer may fidget a moment to think that their jeans or underwear contain cotton from genetically engineered plants, but the response is less visceral than the discovery that their breakfast or lunch contains ingredients derived from genetically engineered crops.

The fiber system is simpler than the food system, since transgenic trees may be developed by their primary harvesters and processors. There are fewer players, fewer products, fewer species and culture methods, and simpler value chains. This simplicity may make it easier to design products and develop value chain relationships with more aligned interests than the current path of genetically engineered seeds from biotechnology company, to farmer, to processors, to traders, to food companies, to supermarkets, and to consumers and restaurants.

Time may also be on the side of genetically engineered trees. The mindset of the forest product industry is much longer than that of the crop industry, which is based in annual cycles, and it is normal for forest companies to think in 5-, 10-, and 20-year time frames. The slow growth of trees ensures there will be no fast product introduction; and delays of a year to get the best transformant or to choose a proper genetic background will have less of an impact on the rate of tree commercialization. Tree scientists are also a patient lot. There is no time or financial pressure from the public markets on the industry to meet or exploit the promises of the technology in any near time frame.

Table 3. Framework conditions for a GE tree market.

- Social utility is the foremost concern.
- Design for the environment is of highest priority.
- Business motives and plans are transparent.
- Business communications and actions are aligned with investments.
- Stakeholders are engaged in decision-making.
- Private and public investment are balanced.
- Research in ecological impacts of transgenic tree plantations.
- Value capture and business strategy is not based in patents.
- The first developed traits are output traits.
- Stakeholders that perceive risks can make choices and perceive benefits.
- Target markets have appropriate regulatory capacity.
- Region-specific products are developed.
- Technology is applied to serve needy populations and protect biodiversity.

Balanced against all these comparisons that make commercialization of acceptable genetically engineered trees more probable, is the symbolic value of forests and trees. A treatment of the symbolic history and value of trees and forests and is beyond the scope of this essay. The American biotechnology companies underestimated the cultural symbolism and importance of agriculture in Europe, and biotechnology activists underestimated the desire many developing countries have to use biotechnology or to self-determine their own technological choices. Timber product companies may be in for a shock at how the public feels about its trees, especially if the genetically engineered tree does not directly connect to the protection and renewal of forests. The typical public opinion survey sponsored by the biotechnology industry asks about possible acceptance of benefits and not, "Would you like a plantation of genetically engineered trees in your backyard?" Still, the framework conditions for a market for transgenic trees are fairly clear and conceivable when abstracted from our experience with genetically engineered crops (Table 3).

THE QUALITY OF OUR ANSWERS DEPENDS ON THE IMAGINATION OF OUR QUESTIONS

The world's most biodiverse forests are threatened by development, conversion to agricultural lands, ore and oil extraction, over-hunting and over-logging, global climate change, and destruction of water resources. Billions of people in the world have pressing needs for energy, paper, and materials that are needed features of economic development, improved health, literacy, and commerce. And forests play central roles in protecting watersheds, purifying air and water, stabilizing climate, protecting species diversity, offering cultural and spiritual value, and supporting tourism and recreation. In a world whose population is due to grow by a third in the next 25 years (and chiefly in less-developed countries), imaginative solutions with a place for technology will be needed to meet global needs for water, materials, energy, and paper. This will require keeping sight of the sustainable forestry goals beyond the transgenic trees.

This author has never seen a deep analysis of the role of tree biotechnology that considers the values that forests and trees deliver, in the context of specific nations, social values, regulatory structures, and economic scenarios. We cannot question the utility of genetically engineered trees without a serious question of "compared to what?" There is opportunity to develop sustainable silviculture that is part of integrated management of productive forests, working landscapes, and protected forests to maximize ecosystem goods and services for all human uses. Tree plantations do not have the legacy of crop agriculture, such as a history of monoculture or a system of production and production inputs, and they might be designed for biodiversity.

During the next five years, the public and private sector will make critical decisions about investment in genetically engineered trees. Risk or benefit is not intrinsic to genetic engineering. The experience with the genetic engineering of crops has proved that cultural, environmental, and economic risks and benefits are each conceivable and are each achievable with genetic engineering. Tree biotechnology has not yet crossed the proof-of-concept threshold for either risk or benefit, and the traits and species to be chosen for commercial modification remain uncertain. Whether and how genetic engineering can equitably and safely serve the needs of sustainable development remains to be seen. We can make wise choices as citizens, scientists, and businesspeople about how to develop the technology, with what safeguards and to what ends. The thoughtful, creative, and rigorous consideration of this question should be limited only by our knowledge in the moment and not by the imagination and courage to envision and realize fair processes, shared benefits, and a sustainable future.

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The Ethics of Molecular Silviculture

Paul B. Thompson

ABSTRACT

The paper provides a general discussion of ethics as applied to technical practices. *Ethics* is defined as the explicit articulation of the underlying rationale for engaging in or regulating a technical practice. Recombinant techniques for plant transformation silviculture raise ethical issues largely because they have brought the technical practices of silviculture and plant development before the public eye in a manner that is unprecedented in recent memory. This has placed practitioners in the position of needing to make an articulate and non-technical statement of the rationale—the ethic—that guides the use and development of science and technology within plant and animal sciences. Too often they have been unable to do this. The unfortunate result can be an erosion of confidence and trust in the technical competence of specialists and a ratcheting effect that links ethical issues with the perception of elevated risk. Although it is difficult to propose measures that would constitute a rapid response to this situation, the longer-term need is to develop an ongoing effort to increase the capacity for articulation and communication of the professional ethic that guides the technical practices of silviculture, and to ensure that technical professionals are receptive to constructive criticisms of their prevailing practices.

This paper provides an overview of normative issues associated with molecular silviculture. Following a brief clarification of terminology, ethical issues are broken down into four categories: religious or metaphysical concerns, environmental ethics, social ethics and professional ethics. Contested issues in each category are briefly reviewed, followed by a succinct statement of the author's considered views.

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TERMINOLOGICAL INTRODUCTION

The relevant practices of molecular silviculture include especially the use of recombinant methods for plant transformation within research, pro duction, and conservation contexts, but also the development and application of genetic techniques such as genomics and informatics that need not involve plant transformation. This definition leaves open some amount of ambiguity regarding the scope of the practices under review. However, it is ambiguity over the term *ethics* that is far more likely to create confusion or misunderstanding. As such, some pains will be taken to clarify the intended scope of ethics, and the role that the academic discipline of philosophy can play in elucidating the ethics of any technical practice.

Practices involve ethics insofar as they are understood to serve larger purposes or to be valuable in themselves. To examine the ethics of a practice is to investigate how the practice can be understood to be done well or poorly, to inquire into the purposes or value of the practice, and to articulate standards for performance, justification, or evaluation of the practice. Some people reserve the word 'ethics' for issues involving conflict of interest or sexual misadventure, and the recent spate of interest in research ethics has focused attention on issues of scientific misconduct. The term is also associated with cultural mores, religion, and even irrationality in some quarters. Philosophers have developed a somewhat more specific interpretation of ethics that stresses the explicit formulation of justifications, desiderata, and codes of conduct. Each involves a set of claims intended for use in deriving statements that specify a particular policy or a particular course of action ought to be followed. Philosophical ethics (or moral theory) is the study of how ethical principles can be systematically used to develop logically consistent and conceptually coherent ethical arguments. The claim that forest policy should promote efficient use of resources is, thus, an ethical principle because it advocates the norm of efficiency as a criterion for the formation and justification of management plans and forest policies.

Philosophers interpret disputes over the legitimacy or justifiability of a given practice as involving competing or incompatible ethical principles. This is, perhaps, contrary to those who presume that the word 'ethics' signals a particular class of special considerations, distinct from those that would be characterized as 'social' or 'economic'. For example, consider a hypothetical dispute between someone holding the view that tree biotechnology is justified because it promotes efficient use of natural resources and someone holding the view that tree biotechnology is unacceptable because it is unnatural. As philosophers see it, this is not a dispute in which only one person is making an ethical argument. Both these points of view involve ethical principles, and one role of philosophy is to spell out the manner in which conflicting ethical principles contribute to each of these contrasting points of view.

There has arguably been a one-sidedness to press coverage about the ethics of biotechnology. The word 'ethics' is generally associated with viewpoints that are critical of using biotechnology, and often unilaterally opposed to all uses of recombinant techniques for plant and animal transformation. Although these critical viewpoints are often countered by sources who cite potential benefits from recombinant techniques, these voices advocating the weighing of risk and benefit are not represented as expressing an ethical perspective. Yet from the standpoint of philosophical ethics, arguing for a practice by citing the relative value of its costs and benefits is a time honored and logically coherent approach to ethics.

Although philosophers can be expected to use a common vocabulary in discussing ethical issues, it is still the case that the judgments and opinions that individual philosophers develop are somewhat personal. As such, philosophical literature in ethics often consists in the statement of a particular viewpoint or evaluation, followed by an argument intended to support the conclusions expressed therein. In this context it is important to cover a wide range of issues in a succinct fashion, but it is also important for a philosophical author to be as unambiguous as possible in communicating the judgments that he or she has reached on the issues in question.

The balance of the paper describes the four previously noted domains of ethics in which issues arise in connection with molecular silviculture. Each section includes a review of the ongoing debate. In each section, the review is followed a very concise statement of my own views. Space constraints do not permit extended arguments on the topics in question.

RELIGIOUS AND METAPHYSICAL ETHICS

The first question that leaps forward when the subject of ethics is broached in connection with molecular genetics is whether this whole area of science and technology doesn't transgress some sort of boundary or absolute prohibition. And even if simply learning about the genes is permitted, some clearly believe that moving genes through recombinant techniques is not. This is, in other words, the 'playing God' domain of ethics. There is neither doubt that many people react to the prospect of altering the genetic make-up of living things with repugnance, nor difficulty in understanding why they might tend to express their reaction by questioning the ethics of such practices. In the case of issues made familiar by press coverage of human cloning and stem-cell research, grounding these reactions in terms of specific religious norms is a fairly straightforward process. However, it is surprisingly difficult to articulate why the alteration of plants, including trees, would transgress generally recognized ethical boundaries, or how it would relate to well-established religious traditions.

Although I can certainly imagine a theological/metaphysical conception of nature that ascribes certain intentions or purposes to the fabric of reality, and I can imagine that those intentions and purposes might be inimical to biotechnology, I am frankly not the philosopher to offer a sympathetic portrayal of such a viewpoint. In fact, my reading on the ethics of biotechnology suggests that most people who are inclined to worry about this possibility are actually somewhat reluctant to make bald statements about God's intentions or purposes. Instead, they refer ambiguously to the sanctity of life, or defend the repugnance that many people feel on first learning about the new genetics (see Thompson 1997, 2000).

I do not want to imply anything but respect for people who offer these points of view. In fact, I take great comfort in the fact that they *do not* profess to be on the hotline to God in deriving their concerns about genetic technology. Nevertheless, my own view on these issues is that the humility and cautiousness endorsed by those who take such perspectives is more appropriately expressed as a component of environmental or social ethics rather than as a specific reaction to the fact that recombinant techniques are being used. There is, in my view, a large and growing gap between the language that we use to make sense of the phenomenal world of daily life and the language of molecular biology. The moral wisdom that we derive from our religious and cultural traditions is fitted to a world of rocks, trees, and flowers. While we should be cautious about discarding that wisdom, it is very difficult to see how it translates to a world of DNA, coding and non-coding sequences, and micro-cassettes. Those who presume that phenomenally derived norms bearing on topics such as heredity or living appropriately in nature can be transcribed literally into talk about genes, proteins, and molecular life processes are guilty of naive genetic determinism. Unfortunately, too many scientifically trained people are guilty of this—but that is an issue for professional ethics, and I must not get ahead of myself.

Before leaving the religious and metaphysical domain, I want to stress that I am not dismissing these issues. I am not saying that the biologists' language is a true description of reality, while ordinary or religious descriptions of the phenomenal world are false. Rather, I am saying that I do not how to build the bridge between these two kinds of language. As such, I do not know how to apply norms of humility and respect for life at the molecular level. As will become evident shortly, I do think that we can build bridges that relate to some specific environmental and social concerns. I am not sure whether it is important to build bridges in the domain of religious ethics, but if it is, that work is surely in its infancy so far.

ENVIRONMENTAL ETHICS

There are, I think, a lot of open questions about the environmental risks of transgenic plants, and I would think that given the lengthy reproductive cycle of trees, these questions are particularly vexing in the area of silviculture. The main focus of environmental risk from transgenic plants has been the potential for unintended impacts on so-called non-target organisms: gene flow to close relatives, and inadvertent effects on habitat that affect other forms of plant and animal life. Although these are inherently empirical questions, the framing and analysis of environmental risks involve a number of value judgments that require a sophisticated mix of science and ethics. The question of whether to minimize Type I or Type II statistical errors is one example. The question of which populations to specify when formulating relative probabilities is another. Are we interested in transgenic trees as a class? Should they be compared with all non-transgenic trees, or should we be making a comparison between trees that are genetically similar, save for the transgene of interest? Do impacts on land use count in the environmental risk assessment, even though human decision making would be involved in bringing them about? These are not purely scientific questions, and there should be a more explicit and conscientious effort to address these ethical questions in technical debates about environmental risk.

And then, of course, we get to the question of whether these risks are acceptable. At present, the debate has stressed uncertainty. Does the open-ended nature of these questions provide a reason to block either research or commercialization of transgenic trees? There are environmental activists who think that uncertainty provides the basis for sweeping argument against transgenic silviculture. They often link their argument to the precautionary principle. Although the precautionary principle can be formulated in various ways, its ethical importance consists in the way that it offers an alternative to norms or decision rules that promote risk-taking whenever expected benefits exceed probable losses. A precautionary approach would differ in that losses associated with environmental damage are treated as a special case on any of several grounds. For example, one might argue that ecological complexity or the relative weak predictive power of ecological models provides a reason to expect that environmental consequences may be much worse than predicted. The irreversibility of environmental outcomes are also cited as reasons to weigh possible losses much more heavily than expected benefits. In both cases, advocates of a precautionary principle would demand a higher standard of evidence for expected benefits than for possible environmental hazards (see Raffensperger and Ticknor 1999).

Although I endorse a precautionary approach in environmental policy, I do not think that it entails a sweeping indictment against biotechnology. The key to my judgment is that even a precautionary approach requires one to evaluate a proposed course of action in comparison with its alternatives. If the alternative to tree biotechnology is that the human species will desist from all use of forest products, precaution might weigh in against biotech. The problem, of course, is that abolishing all human use of forest products would involve such extensive costs that it is not actually a feasible alternative at all. So the alternative to tree biotechnology may actually be an unacceptably exploitative expansion of current practices in industrial forestry. If this is the case, then precaution may actually weigh in favor of transgenic trees. My viewpoint on the environmental ethics of molecular silviculture is that it depends on some background and contextual elements of forest policy, and I need to hear more about it before I could form a firm opinion.

There is also an even more general set of issues in environmental ethics. There has been a tremendous amount of ink spilled over the debate between anthropocentrism and ecocentrism in environmental ethics, and this debate is often traced back to the philosophical conflict between Gifford Pinchot and John Muir over the future of American forests. Pinchot is portrayed as a figure who saw wilderness as deriving all its value from the various uses—including recreational uses—that humans make of it. Muir is portrayed as someone who believed that forests, trees, and wilderness were intrinsically valuable, irrespective of any use that humans made of them. Clearly, this debate continues to resonate throughout forest policy (see Norton 1991; Callicott and Nelson 1998).

Does this debate have any bearing on tree biotechnology? My own view is that its bearing is rather indirect, and that certainly the anthropocentrist/ecocentrist divide does not translate directly into *pro* and *con* positions on tree biotechnology. Only someone who, taking Muir much further than Muir himself would have gone, argues against all human use of trees would conclude that absolutely every conceivable application of tree biotechnology is impermissible. Only someone taking Pinchot much further than Pinchot himself would have gone could think that the impact of tree biotechnology on protected wilderness areas is ethically irrelevant. This brings us back to the issues we started with: the environmental risks of genetic engineering on non-target organisms. It is certainly possible that different environmental values will lead people to frame questions of risk assessment in different ways, and that is one reason why non-scientists need to be included in the process of environmental risk assessment.

SOCIAL AND POLITICAL ETHICS

Many of the activists who have opposed biotechnology in agriculture ground their opposition in a socio-political argument. I will sketch the terms of this argument briefly, though I will say at the outset that, in my view, the considerable merits of this argument as a case for the reform of our technology policy do not translate into persuasive reasons for singling out genetic technologies. Critics of biotechnology in agriculture allege that it is a tool for increasing the control that a few corporations hold over the entire food system. They see biotechnology as a weapon being wielded against poor farmers in the developing world, and as a token in a process of globalization that is intensifying the economic power of multinational companies and international capital.

This is a complex argument in its details, but there are at least four important components to it. One is that the period of the late 1980s/early 1990s clearly did see a considerable consolidation within major seed, agrichemical, and forest products companies, as well as the pharmaceutical industry. This consolidation was sparked by industry's judgment that genetic technologies would be key sources of profitability in the future, and that capturing these profits would depend upon vertical integration of technology discovery and delivery processes. Although economists debate whether this consolidation has created monopoly power within the life-science industry, the sheer volume of activity in mergers and acquisitions throughout this period could not fail to have captured the attention of anyone interested in economic inequality (Teitelman 1989).

Second, U.S. law for intellectual property changed in the 1980s, allowing for an expansion of patent rights over genes, gene processes, and even whole organisms. This displaced the Plant Variety Protection Act, which was weaker both in the sense that it provided exemptions for researchers and for growers propagating plants for their own use. Thus, in addition to industry consolidation, the bigger, consolidated life-science companies had new legal tools at their disposal for concentrating economic power and exerting control (Fowler 1995).

Third, there was a simultaneous shift in the relationship between industry and academic research. In part, this was simply a result of the first two factors. With consolidation among their industrial partners, academic researchers would have found themselves working with a smaller number of firms, even if their actual collaborations with industry had remained unchanged. Academic researchers also found themselves needing industry partners in order to have freedom to operate within the new era of industrial patents. Some have also argued that the nature of biotechnology has tended to blur the distinction between research and development. The need to acquire patents entered life science departments at universities in a new way, as well, making academic departments seem like private companies to outsiders. The net result was at least the perception that publicly funded, putatively not-for-profit academic science was pretty much indistinguishable from profit-seeking industrial product development (see Kenney 1986; Kloppenburg 1988).

Finally, these events were occurring at a time when economists and sociologists had recently completed new analyses of the way that increases in the efficiency of production technology were linked to socioeconomic changes in rural areas. The so-called technology treadmill was a staple of social science analysis throughout the 1970s. This analysis showed how more efficient production technologies fueled a process of change in the structure of farming, leading to fewer and larger farms. This transition was coupled with a decline in the need for rural service industries and a gradual but inexorable economic decline in rural areas. The theoretical techniques for predicting structural change were applied to some of the early products of biotechnology, and this considerably undercut support for them, particularly among advocates of poor and small farmers. The analysis was also applied retroactively to 'Green Revolution' technologies of the 1960s, resulting in a considerable cooling of enthusiasm for productivity enhancing technologies in the developing world. Again, biotechnology just happened to come along at a time when social scientists were applying these methods to ex ante case studies (see Kalter 1985). Although forestry is different in some respects, it is not wholly different, and the timing of new biotechnologies coincided with a new level of consciousness among economically disadvantaged producers about the effects of technology on their interests.

The combined upshot of these four factors was that biotechnology became the poster child for those who see technology as a force driving modern societies toward economic and political inequality. My own view on the social ethics of technical change is actually very close to that of Andrew Feenberg, who describes himself as a left-leaning pro-socialist critic of capitalism (Feenberg 1999). Feenberg believes that technological innovations have indeed tended to serve the interests of capital throughout history, but he also believes that this has primarily been because of the way that owners of capital have been linked to the developers of technology through social networks. In most cases, it would be possible to have the benefits of new technology without the socially destabilizing inequalities, if only the developers of technology could be linked in networks with comparatively disadvantaged people. Thus, what is needed is a political reform of the social infrastructure for developing technology, not opposition to any particular form of technology itself. Although I've never thought of myself as pro-socialist, and though I think the details of any reform will prove to pretty complex, I find myself in substantial agreement with Feenburg's social ethic for technology.

Yet none of this really provides an argument against tree biotechnology. The implication is that those who are opposing biotechnology for reasons of social ethics are chasing the cape, when they should be after the bullfighter. Now, I must qualify my remarks by saying that I don't want to ban corporations or the profit motive, nor do I want government ownership and control of technology development. As I said already, the details will turn out to be pretty complex. But in each of the four elements described above, it is the social networking far more than the use of gene-based or recombinant techniques that leads to the unfortunate social results. We could put an end to biotechnology tomorrow and it would not improve the situation with respect to economic inequality one iota.

PROFESSIONAL ETHICS

And this brings me to my final domain. For almost a hundred years, the professional ethic in the life sciences has been to avoid ethical issues when at all possible. Life scientists came by this ethic honestly and for good reason. The ideal of scientific objectivity became crucial to the establishment of rigor and credibility in scientific disciplines. Entanglement in religious debates over evolution and abortion came to seem less and less relevant to the conduct of science on a day-to-day basis. Nevertheless, by absenting themselves from any discussion of the social networks in which their work is applied and the technologies that are adapted from it, life scientists have adopted an ethic that permits powerful actors to use science silently in the extension and exertion of their power. The uses to which science has thus been put are often quite defensible, and have in many cases been progressive. Yet even in these cases, I submit that the quietness of the alliance between science and economic power is distressing.

Ironically, the very quietness of the life science community is coming to undermine the very objectivity and credibility that a previous generation's professional ethic was designed to ensure. There is, I submit, a feedback mechanism between the quietude of life scientists with respect to the social implications of technology and the public's willingness to place confidence in their opinions with respect to environmental risk. Environmental activists are networked with social activists in attempting to constrain the growth of global corporate power. They are bound to overhear some of the indictments raised against biotechnology in these quarters. The silence of the life science community with respect to such issues can be deafening. The next inference is unfortunate, in my view, but not altogether unexpected. It is implicit in the question, "How can people who are so closely allied with corporate interests when it comes to social issues be trusted when it comes to environment?" And then there is one more inference that gets made: "Isn't it dangerous to leave the future in the hands of such people?" In this way, the silence of life scientists on social issues are translated into positive allegations of environmental risk (Thompson and Strauss 2000).

Now I must be as clear as possible. I do not believe that life scientists as a whole are in league with corporate interests, nor do I believe that corporations are evil or even that their interests are antithetical to the social ends I support. I certainly do not believe that life scientists' failure to become involved in debates over the social control and socioeconomic impact of biotechnology contributes to environmental risk. What I am saying is that these are fairly natural inferences for people to make. I in fact believe that these inferences have substantially frustrated the accomplishment of both environmental and social causes that I strongly support. The expenditure of goodwill and intellectual resources in opposing biotechnology is, in my view, a perfect waste of energy and money by people whose general values and aims I endorse. I wish that I were more articulate and effective in making the case for my view among environmentalists and social activists. But I am also saying that an ethical failure among life scientists has contributed to this unfortunate result, as well.

I do not believe that science and technology automatically translate into socially beneficial outcomes. If the outcomes are to be beneficial, there must be conscious and deliberate work at building the social networks and thinking through the environmental impacts. Undertaking such conscious and deliberate work is, in my view, a needed and too often lacking element in the professional ethic for the life sciences. The symposium we are currently involved with is a notable and important exception to this general trend, and I hope that my remarks will be taken as encouragement to follow through on the work that has begun here.

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Ethical and Social Considerations in Commercial Uses of Food and Fiber Crops

Sandy Thomas

Abstract

The introduction of genetically modified (GM) crops into the environment and food chain in Europe has been highly controversial. The prospect of the predicted growth in GM crops over the next 10 years was greeted with outrage and unease, especially compared with the near-indifference shown by most consumers in Canada and the USA. Underlying this reaction in Europe have been concerns about possible harm to human health, damage to the environment, and unease about the 'unnatural'. The introduction of GM crops was perceived by many as the imposition of new and uncertain technology, which did not offer any obvious benefits. In particular, there have been fears over the use of antibiotic-resistance marker genes and the possibility of increasing and unpredictable exposure to allergens. Concerns that herbicide-tolerant crops might encourage use of broad spectrum herbicides and the emergence of herbicide-tolerant weeds, and that insect-resistant crops might damage non-target species, were also widespread. There has also been unease about the commercial exploitation of the technology, particularly in relation to intellectual property issues. It is not yet clear whether the extensive patenting that has taken place in plant technology has had a restrictive effect on research. In Europe, the debate has been focused almost entirely on GM food crops, and there has been relatively little discussion on the issues raised by the development of forest biotechnology. Most concerns mentioned above are ethically based and concern principles of rights and general welfare, as well as unease about our relationship with the natural world. There has been broad acceptance of living with a considerable amount of human intervention, but GM technology is perceived by some as a 'step too far'. These reactions raise important public policy issues. One objective of public policy is to understand these concerns more fully and to take account of them when regulatory guidelines are being drawn up. The outcomes of GM debate in Europe have been profound: a de facto moratorium, a decline of commercial investment, increased distrust of scientific advice, and increased anxiety about new technologies. This paper will consider the implications of the GM crop experience for the development of forest biotechnology.

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The introduction of genetically modified (GM) food crops into the environment and food chain has become highly controversial in the UK, much of Europe, and other parts of the world. The idea that GM crops for food and fiber will form a large proportion of the plants grown by farmers in the UK over the next 10 years has been met with a wide range of reactions, from outrage and unease to acceptance. By contrast, consumers in the United States and Canada have greeted their introduction with near-indifference. The principal objections to GM crops and the food products made from them have concerned possible harm to human health, damage to the environment, and unease about the 'unnatural' status of the new technology. Concerns over human health have focused primarily on the use of antibiotic-resistance marker genes, the possibility of increasing and unpredictable exposure to allergens, and the uncertainty about the long-term effects of novel combinations on human health. Alarmist media reports surrounding Pusztai's experiments, which claimed to demonstrate immunological damage to rats when fed GM potatoes, also served to heighten concerns. Environmental concerns have arisen on a number of counts. There have been fears that GM herbicide-tolerant crops might encourage farmers to use more broad spectrum herbicides with a negative impact on insect and bird life. The risk of transfer of transgenes to wild populations and the possibility that insect-resistant crops might cause damage to non-target species has also been raised. Many consumers in the UK have also objected to what they see as the imposition of a new and uncertain technology that does not appear to offer clear benefits.

In 1997, the Nuffield Council on Bioethics decided to set up a Working Party to consider the ethical and social issues raised by the anticipated introduction of GM crops. At that time, there was relatively little public interest in the subject. By the time the Council published its report in 1999, the public debate in the UK was at its height. Since then, the concerns of consumers about the safety of GM crops have led to a de facto moratorium on their use in the European Union (EU) and their disappearance from the food chain. The fact that these events have occurred in the absence of evidence implicating GM crops as a risk to human health or to the environment illustrates the importance and the potency of public opinion when introducing new technologies. Today, forestry is poised to adopt GM technology. In doing this, there will be opportunities to achieve breeding goals more rapidly and the promise of genuinely novel varieties that could not be produced by other means. Whether GM trees are successfully adopted or not, will depend in part on how they are perceived by the public. There are, without doubt, lessons to be drawn from the wide range of ethical and social issues raised by GM food crops. In this paper, these issues are considered within the context of the UK debate.

THE ETHICAL CONTEXT FOR GENETIC MODIFICATION

Ethical Principles

The development of GM plant technology broadly raises two kinds of issues: the scientific and the ethical. Science is concerned with understanding the world in which we live and in particular the causal relationships that shape that world: for example, the association between genes as a molecular sequence and the characteristics, such as resistance to disease, that genes express. If we are to alter or change the characteristics of plants in an informed way, then an understanding of such causal patterns is necessary. By contrast, ethics is concerned with what we ought or ought not to do. Ethical principles provide standards for the evaluation of policies or practices. For example, they may guide us to decide that it would be wrong to carry out a certain genetic modification because to do so would threaten human health or harm the environment. Because it may be scientifically feasible to undertake a particular experiment or introduce a new type of crop for commercial planting, it does not follow that it would be ethically right to do so. To decide what it is right or permissible to do involves, therefore, bringing together our scientific understanding with our ethical principles to decide what we should do given the capacities for genetic modification that have been developed.[1]

Practical reasoning involves weighing up or balancing the benefits of a technology like genetic modification with its potential harms or disadvantages. However, few questions of practical reasoning about policy or practice can be dealt with in a simple form. Supporters of GM plant technology claim that it will raise agricultural productivity, assist the development of safer, more nutritious foods with a longer shelf-life, and contribute to the goal of increased food security for the poor in developing countries. Against these claims, we must set the claims of those who assert that not only is GM food technology a threat to human health and the environment, but that its introduction will raise the profits of the private sector, whilst at the same time depriving poor producers of primary commodities access to markets and to the new varieties of seed. Whether GM technology is morally acceptable is a matter of the plausibil-

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[1] *Nuffield Council on Bioethics. 1999. Genetically Modified Crops: The Ethical and Social Issues. Nuffield Council on Bioethics, London.*

ity of these factual claims and their importance in the light of moral principles.

Welfare, Rights, and Justice

There are three main types of ethical principle that are relevant to the evaluation of policies or practices. The first is a principle of general welfare, which requires governments and other powerful institutions to promote and protect the interests of citizens. The second principle is the maintenance of people's rights, such as their rights to freedom of choice as consumers. The third is the principle of justice, and it requires that the burdens and benefits of policies and practices be fairly shared among those who are affected by them. When we consider the introduction of a new technology, such as genetic modification, we can ask a series of questions in the light of these three general principles. Will the technology promote the general welfare by improving food safety or by reducing the use of chemical pesticides in the environment? Or will the technology pose unknown risks for consumers and the environment that we would be wise not to take if we are concerned about general welfare? What implications does the technology have for the rights of consumers, for example, the right to be informed about the food one is eating or the environmental impact of a particular product that one is buying? What implications are there for the rights of scientists to be free to conduct their research in ways that protect their intellectual integrity? Finally, we pose a series of questions derived from a concern with the principle of justice. Who will be the principal beneficiaries from the introduction of genetic modification and what obligations do they have to compensate the losers?

In its report on GM crops, the Nuffield Council did not draw a sharp distinction between ethical concerns and social issues. On the one hand, ethical principles concern the social framework within which society lives. On the other, there is a need to be aware of the social and technological background against which ethical issues are discussed. Scientific, ethical, and social issues cannot be wholly separated from each other, nor should they be. It is, broadly speaking, an ethical choice to apply scientific knowledge in the hope of improving the human condition. Different societies have set different values on the acquisition and use of scientific information; trying to use scientific knowledge for what Francis Bacon called "the relief of man's estate" may seem an obvious choice, but it is not an inevitable one. It is the ethical basis of the regulation of commercial development and production of GM crops and the promotion of genuinely useful research by government action that mostly concerns us.

Natural versus Unnatural

In setting out the three main types of ethical principles that are relevant to the evaluation of GM technology, there is a need to consider one substantive issue, namely the ethical status of the natural world itself. GM crops do not prompt questions about the rights or welfare of plants, in the way that animal experimentation raises questions about the rights of animals. They have, however, provoked a reaction, particularly in Europe, that is difficult to place within the ethical framework of welfare, rights, and justice. Some people perceive GM crops as 'unnatural' and those who disapprove of their introduction for this reason are among the strongest critics. For all the decline in formal religion, there remains a deep-rooted belief that society 'tinkers' with nature at our peril.

Others have argued that it is unethical to treat nature in an 'industrial' fashion, not merely because of the unfortunate consequences of doing so, but because they believe it to be inherently wrong. Whereas the first of these concerns can be accommodated under the principle of the general welfare, the second makes 'the environment' an object of ethical concern, regardless of how the environment affects the interests of human and other animals. GM crops thus raise ethical issues about the rights and wrongs of the ways we affect the environment that are especially difficult to analyze and resolve. The government of a modern democratic society is required not merely to accommodate the deeply held moral convictions of its citizens, but to treat them with respect. However, such convictions, on difficult issues such as research on embryos, are usually held by minorities no more numerous than those who hold the opposite conviction. Governments cannot legislate or regulate by making these convictions the basis of law, but have to pursue policies that can command something close to a reflective consensus. Thus, safety, health, economic well-being, and the avoidance of environmental degradation are commonly the goals of government policy.

The Precautionary Principle

The concern of government with the welfare of its citizens underlies much current regulatory practice. One of the duties of forestry companies introducing GM trees, whether in experimental trials or for commercial use, would be to ensure that they do no harm or, that any harm is so slight as to be broadly acceptable. The regulatory system for GM crops and their products in the EU is predicated on this basic proposition. The prevention of harm is sometimes extended to promote the adoption of the *precautionary principle*. This principle sets the avoidance of harm to consumers and the environment at the head of the list of regulatory goals. However, the universal adoption of the precautionary principle risks an imbalance between the avoidance of harm and the achievement of a positive good.

The precautionary principle can be viewed as a simple, welfare-based principle.[2] As such, it raises familiar problems, of which the most important is to define the conditions under which the avoidance of harm should take priority over the attempt to do good. Common sense suggests that the development of crops that substantially reduce hunger or improve nutrition in the developing world would justify running the risk of modest damage to the interests of well-off consumers or the environment. However, critics argue that GM crops will bring benefits only to the producer, not to the consumer, and that any risk of harm cannot therefore be justified. Both views imply that it is right to balance the good achieved against the harm imposed. A stringent interpretation of the precautionary principle would preclude such balancing. It may, however, be best interpreted, not as part of a cost/benefit calculation, but as a principle governing how such calculations should be made. The principle does not yield very definite prescriptions, but does indicate caution for those who would introduce new technologies.

ETHICAL ISSUES AND THE ENVIRONMENT

Public concerns about the environment have been increasing over the past 40 years. Most of these concerns are ethically based and the majority center on welfare, that is, the welfare of present as well as future generations. Clearly if the resources within our environment became so badly damaged that it was not possible to sustain human, animal, and plant life, the loss of welfare would be infinite and the moral responsibility of those who brought about such environmental disasters undeniable.

Welfare

Another type of welfare concerns the pleasure that people derive from living alongside the natural world, even when they may not have the opportunity to visit it. The pleasure may extend to simply ‘knowing that it is there’ and could be visited. There are also issues of rights here. One particular conflict is between the rights, for example, of forestry companies to exploit the environment and the rights of others, such as environmentalists, who might wish to preserve the environment as an amenity. Other welfare considerations that relate to the environment in a more straightforward way are concerned with the direct consequences of genetic modification. The main concern here is that we risk damaging the economic and amenity resources of the environment. These concerns are closer to the traditional role of public policy in ensuring safety.[3] However, one of the difficulties in assessing the potential risks of new technologies is that there is often an absence of agreed measures of the relative seriousness of different kinds of potential harms.

Rights

The genetic modification of plants also raises questions of rights. For example, do forestry companies have a right to pose environmental risks, however small, in pursuit of benefits, whether these are profits, consumer benefits, or both? In general, individu-

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[2] *Nuffield Council on Bioethics. 1999. Genetically Modified Crops: The Ethical and Social Issues. Nuffield Council on Bioethics, London.*

[3] *Krebs, JR, et al. 1999. The second Silent Spring? Nature 400: 611– 612.*

als and others have the right to risk their own well being, but not that of others. A balance has to be struck between, for example, the legitimate desire of forestry companies to create wealth, the needs of consumers, and the continuing need to maintain a sustainable environment for future generations.

THE CONTEXT FOR THE UK GM DEBATE

In the UK debate on genetic modification of crops, four constituencies proved to be of particular significance. These were the non-governmental organizations (NGOs), consumers, the public sector researchers, and the private sector in the form of the seed and agrochemical industry.

The NGOs

The NGOs who were actively campaigning against the introduction of the new technology had, in some cases, a wider environmental agenda, of which GM crops were but a part. At a time when public confidence in the government scientific advisory system was at an all-time low, some of the NGOs, particularly Greenpeace and Friends of the Earth, were able to capture considerable public sympathy. Both of these NGOs and others ran highly professional campaigns, which were highlighted by the media at a time when the UK Government was relatively silent on some of the issues. Although at a later stage in the ongoing debate some of the NGOs lost public support through their repeated destruction of field trials, their impact in the absence of specific evidence about the possible risks of GM crops was substantial.

The Consumers

Consumers in the UK were particularly influential in the debate because the food retailers were particularly responsive to their views. Once doubts were raised about the safety of GM food in the UK supermarkets, fueled by alarmist media reports and a lack of discriminatory food labeling, consumers were quick to voice their concerns. Their lack of confidence in government advisory bodies after the BSE fiasco, the perceivedlack of transparency in labeling GM food products, and the lack of clear benefits were potent factors, which combined to erode public confidence at a rapid rate. Retailers effectively removed approved GM food ingredients and products from the supermarket shelves and replaced them with non-GM supplies.

The Private Sector

The multinational companies inevitably played a significant role in the debate. As agents for the development of the new technology, they were vilified by the majority of NGOs and viewed with distrust by much of the public. The role of Monsanto in alienating the UK consumers, a key factor in sparking the controversy, has been widely discussed elsewhere. The initial non-segregation of GM from non-GM foodstuffs was a critical and costly error leading to a lack of consumer choice, which mattered to the consumer who was concerned about safety. The fact that the main culprit was a ubiquitous food ingredient in the form of GM soya meant that the effects were far reaching. The multinationals were moreover portrayed by some as being in pursuit of profit, despite uncertainties over the safety of the technology, both for human health and the environment. There were also concerns over issues relating to ownership of and access to the technology.

In the case of patents for GM crops, two public concerns have been visible.[4] One has been with the legitimacy of ‘owning life’. Various interest groups have been campaigning, on ethical grounds, against the concept that property rights can exist in genetic material or activities associated with it.[5] While some of these objections can be attributed to deeply held beliefs, in others, a misunderstanding of the patent system may play a part. The other concern has been with the patenting of GMs and the research techniques associated with the development of GM crops. Patent holders may be reluctant to license patents with broad claims to key technologies to their competitors or to public-sector research

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[4] *Nuffield Council on Bioethics. 1999. Genetically Modified Crops: The Ethical and Social Issues. Nuffield Council on Bioethics, London.*

[5] *See Dworkin, G. 1997. Property rights in genes. Philosophical Transactions of the Royal Society of London Series B (Biological Sciences) 352: 1077–1086.*

institutions. Companies may seek patents that will not advance research or production, but that deter competitors and prevent research in areas that threaten their monopolies. In addition, public laboratories are increasingly demanding a royalty on future commercial developments from their publicly funded colleagues in their terms for licensing access to research tools. Consolidation in the agrochemical and seed industry has continued to reduce the list of owners of the important 'enabling' intellectual property for plant genetic modification and plant molecular genetics.[6] There are now around six major industrial groups who between them control most of the technology that gives freedom to undertake commercial R&D in the area of GM crops.[7] There has also been concern over the patenting of DNA sequences and particularly ESTs (expressed sequence tags).[8] The question of patent dependency[9] for partial sequences or where the gene function is unknown is important not only in the pharmaceutical industry, in relation to human genes, but also in the plant science sector, both public and private.

The Scientists

Finally, the fourth grouping that has been important in the UK controversy consists of the scientists, namely those in the public sector. At a time of uncertainty, many looked to the country's scientists for reassurance and impartiality. However, it proved difficult for researchers working in the area of GM to make much of an impact on the debate for two main reasons. First, in the UK (unlike in the USA), the majority of scientists have little or no experience in dealing with the public. Many were reluctant to be drawn into a debate in an area where the public was disaffected and substantially prejudiced against the technology. Second, a number of scientists who had expertise in GM technology were perceived as non-independent because they were participating in research partnerships with industry. The fact that research collaboration with the private sector is increasingly the norm today in many public-sector institutions around the world did not serve to diminish public skepticism.

THE OUTCOMES OF THE UK GM DEBATE

The scope and intensity of the controversy over GM crops in the UK took most people by surprise. In general, over the past decade, the UK public has not been strongly opposed to the development of biotechnology. The strong reactions against recombinant DNA technologies in Germany and Denmark during the early 1990s were not mirrored in the UK. As a result, the UK regulations concerning GMOs were not excessively stringent, and research, development, and production of new GMO-related products was allowed to progress. At this stage, these products were associated with the pharmaceutical sector, which was at an earlier stage of development in the application of GMOs than was the agrochemical industry.

That situation has changed profoundly. Recent public reaction against the introduction of GM crops into the environment and the inclusion of GM ingredients in food has been more intense in the UK than in any other European country and shows little sign of abating. Despite the lack of evidence to show that GM crops threaten our environment or health in new and significant ways, a wide range of organizations have disassociated themselves from GM crops and their products or are considering doing so—major food retailers, agricultural landlords (such as the Duchy of Cornwall), local council authorities, restaurants, and schools. Over the past 24 months, the UK public has not been involved in an informed debate, but rather has been the target of a stream of relentless and negative propaganda.[10] However, the recent decision by Greenpeace to join some UK fringe groups and destroy GM maize trials may prove to be something of a turning point. The UK public is wary of GM food but, one suspects, would not support the wholesale abandonment of the very research that will provide answers to some of the

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[6] *Nuffield Council on Bioethics. 1999. Genetically Modified Crops: The Ethical and Social Issues. Nuffield Council on Bioethics, London.*

[7] *Nuffield Council on Bioethics. 1999. Genetically Modified Crops: The Ethical and Social Issues. Nuffield Council on Bioethics, London.*

[8] *ESTs are partial DNA sequences which represent genes that are turned on in a particular tissue type or organism.*

[9] *There is concern over the extent to which patents on ESTs may impose dependency or 'reach through' to subsequent patent applications with full-length sequences.*

[10] *Beringer, J, and H Wallace. 1999. Natural justice? New Scientist 14 August, p.47.*

questions the technology poses. The future of GM crops in Europe has in a number of ways been postponed, which some interpret as a de facto moratorium.[11] This has resulted in a decline of commercial investment in GM crops. The role of plant biotechnology research in the public sector too, may need to shift in emphasis. There is a legacy of increased distrust of scientific advice, already weakened at the outset, and increased anxiety about new technologies. Elsewhere in the world, GM crops continue to be researched and grown. The United States, Argentina, and China are substantially committed, and a number of developing countries see a role for GM technologies in improving their food security.[12] It is estimated that U.S. citizens eat GM food products at every meal and as yet, after over eight years, no adverse events to health have been reported.

So in conclusion, what are the lessons that the forest biotechnology sector might draw from this protracted and difficult debate? First and foremost, the issues that will be raised by the introduction of GM trees will not be confined to the scientific. Careful thought must be given to how members of the public perceive the impact of existing forestry practices on the environment and how GM technology might change this perception. Issues of rights and welfare for both consumers and producers will need to be considered. There is an ongoing need to build public confidence and trust in the new GM technologies. Progress will only be made if there is transparency and openness in the scientific advisory process for regulating and approving the introduction of the new trees. At the outset, an open dialogue between the various stakeholders to identify and discuss the range of issues raised will help to prevent the development of a prolonged and unbalanced debate in which scientific evidence played a minimal role. It is worth noting that the initial U.S, GM field tests in 1986 and 1987 took place after open discussions among scientists, regulators, farmers, and environmentalists.[13]

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[11] *McCabe, H, and D Butler. 1999. European Union tightens GMO regulations, Nature 400:7.*

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REGULATORY POLICIES

Proceedings of the First International Symposium on
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www.fsl.orst.edu/tgerc/iufro2001/eprocd.pdf

Regulation of Transgenic Plants in the United States

David S. Heron
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ABSTRACT

The Agencies primarily responsible for regulating biotechnology in the United States are the US Department of Agriculture (USDA), Environmental Protection Agency (EPA), and the Food and Drug Administration (FDA). Products are regulated according to their intended use, with some products being regulated under more than one agency. Genetically engineered plants must conform with standards set by State and Federal marketing statutes such as State seed certification laws, the Federal Food, Drug, and Cosmetic Act (FFDCA), the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), the Toxic Substances Control Act (TSCA), and the Plant Protection Act (PPA). There are no national requirements for varietal registration of new plant varieties. The U.S. unified home page for biotechnology has further information (www.aphis.usda.gov/biotech/OECD/usregs.htm).

Within USDA, the Animal and Plant Health Inspection Service (APHIS) is responsible for protecting U.S. agriculture from pests and diseases. APHIS regulations provide procedures for obtaining authorization prior to importation, interstate movement, or field testing of a regulated article in the United States. The regulations also provide for a petition process for the determination of nonregulated status. Once a determination of nonregulated status has been made, the product (and its offspring) no longer require APHIS authorization for movement or release in the US. EPA sets standards for the safe use of pesticides, both chemical and those that are produced biologically. The authority of FIFRA is used to regulate the distribution, sale, use and testing of plants and microbes producing pesticidal substances. Under FFDCA, EPA sets tolerance limits for substances used as pesticides on and in food and feed, or establishes an exemption from the requirement of a tolerance. EPA also establishes tolerances for residues of herbicides used on novel herbicide-tolerant crops.

FDA regulates foods and feed derived from new plant varieties under the authority of FFDCA. FDA policy is based on existing food law, and requires that genetically engineered foods meet the same rigorous safety standards as is required of all other foods. Consistent with its 1992 policy, FDA expects developers to consult with the agency on safety and regulatory questions.

Our joint paper today will be a brief overview of the Federal regulatory framework for the regulation of transgenic plants in the United States. We will also discuss some information that may be relevant for those interested in the development of transgenic forest trees, and we will provide some sources for additional information, much of which is available at agency web sites.

The United States unified home page for biotechnology has further information and links to the agency sites (See http://www.aphis.usda.gov/biotech/OECD/usregs.htm).

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COORDINATED FRAMEWORK FOR THE REGULATION OF BIOTECHNOLOGY

In 1986 the Coordinated Framework for the Regulation of Biotechnology was adopted by federal agencies (see 51 Fed. Reg. 23302; June 26, 1986) to provide a coordinated regulatory approach intended to ensure the safety of biotechnology research and products by using existing statutory authority and building upon agency experience with agricultural, pharmaceutical, and other products developed through traditional genetic modification techniques. The Coordinated Framework is consistent with the conclusion of the 1987 report of the National Academy of Sciences that found that the potential risks associated with genetically engineered organisms should be similar in kind to those associated with traditionally bred organisms.

The Coordinated Framework identified three main agencies: U.S. Department of Agriculture, Environmental Protection Agency, and Food and Drug Administration. The Coordinated Framework further emphasized the need for ongoing interagency coordination mechanisms to ensure that policy and scientific questions would be addressed across agencies. Products of biotechnology are regulated according to their intended use, with some products being regulated under more than one agency.

Table 1 contains some examples of common types engineered plants and which Agency has regulatory responsibility. This information is available at US Unified Home page for biotechnology at http://www.aphis.usda.gov/biotech/OECD/usregs.htm.

FDA Role

As a part of the Department of Health and Human Services, FDA regulates foods and feed derived from new plant varieties under the authority of the Federal Food, Drug, and Cosmetic Act. FDA policy is based on existing food law, and requires that genetically engineered foods meet the same rigorous safety standards as is required of all other foods. FDA's biotechnology policy treats substances intentionally added to food through genetic engineering as food additives if they are significantly different in structure, function, or amount than substances currently found in food. Many of the food crops currently being developed using biotechnology do not contain substances that are significantly different from those already in the diet and thus do not require pre-market approval. Consistent with its 1992 policy, FDA expects developers to consult with the agency on safety and regulatory questions (for further information see http://vm.cfsan.fda.gov/~lrd/biotechm.html). Because of this meeting is focusing on forest trees, we will not discuss food safety reviews in greater detail, but refer interested parties to the citations above.

Table 1. Regulatory responsibility for common types of engineered plants.

New trait/organism	Regulatory review by	Reviewed for
Viral resistance in food crop	USDA EPA FDA	Safe to grow Safe for the environment Safe to eat
Herbicide tolerance in food crop	USDA EPA FDA	Safe to grow New use of companion herbicide Safe to eat
Herbicide tolerance in ornamental crop	USDA EPA	Safe to grow New use of companion herbicide
Modified oil content in food crop	USDA FDA	Safe to grow Safe to eat
Modified flower color in an ornamental crop	USDA	Safe to grow

APHIS Role

Within USDA, the Animal and Plant Health Inspection Service (APHIS) is responsible for protecting U.S. agriculture from pests and diseases. Under the authority of the Plant Protection Act, APHIS oversees the importation, interstate movement, and the field testing, under controlled conditions, of most genetically engineered organisms (termed "regulated articles" in the regulations), particularly most new plant varieties, and assures that these new varieties are as safe to use in agriculture as traditional varieties.

All of those actions require permission from APHIS, in essence a certification that the action will be performed in a safe manner. APHIS authorizes field tests under either permitting or notification procedures that limit the persistence of the viable test plants in the environment at the conclusion of the test. Both procedures require the applicants to meet the same standard of safety in the conduct of the trials.

To date, APHIS has authorized thousands of field tests for more than 50 plant species, but relatively few of these have been tree species. However, APHIS has authorized field tests for transgenic spruce, pine, poplar, walnut, citrus, cherry, apple, pear, plum, and persimmon. The public database for all APHIS authorizations can be accessed at http://www.nbiap.vt.edu/cfdocs/fieldtests1.cfm

As testing of a "regulated article" proceeds, the developer gathers information to confirm that the product has the new intended property, and is as safe to grow in the environment as traditional varieties. Under the APHIS regulations, when enough information is gathered, the developer can petition APHIS to make a Determination of Nonregulated Status.

When APHIS receives a petition, a team of agency scientists begins the review, and the agency announces to the public that the petition has been received. If the review team decides that the petition is complete and ready for full review, the agency makes the petition available for public review and comment. As part of the review process, APHIS considers all available information and public comments before making a determination that a plant will no longer be considered a regulated article.

In these reviews, the APHIS standard is that an organism must not directly or indirectly cause disease or damage to plant, plant parts, or processed products of plants. These include findings that the new plant variety

1. Exhibits no plant pathogenic properties
2. Is no more likely to become a weed than the non-engineered plant
3. Is not likely to increase the weediness of any other plant with which it is sexually compatible
4. Will not cause damage to processed agricultural commodities
5. Is not likely to harm other organisms that are beneficial to agriculture.

Depending on the nature of the modified plant, other relevant issues may be considered, also. Electronic copies of past APHIS assessments (decision documents) can be obtained at the APHIS web site http://www.aphis.usda.gov/biotech/.

As part of the petition process, APHIS also conducts an environmental assessment to ensure that any environmental impacts are not likely to be significant as a consequence of the agency determining that the plant variety or line will no longer be considered a regulated article (nonregulated status). This assessment includes a consideration of the potential effects on the "wider" environmental. This is mandated under the National Environmental Policy Act of 1969, that addresses the general decision-making process for all government actions.

All of these petitions require case-by-case review. APHIS provides users's guides and additional information regarding the petition process at http://www.aphis.usda.gov/biotech/petguide.html. Further information on other aspects of the APHIS oversight of biotechnology can be found on the at http://www.aphis.usda.gov/biotech/

Once a Determination of Nonregulated Status is issued, the new variety may be treated, from USDA's perspective, like any other variety of the crop, i.e., it may be grown, tested, or enter traditional crop breeding programs without any other special oversight with respect to the APHIS regulations. Once any other requirements from other agencies are satisfied, the plant can enter into commerce and be sold. All the normal phytosanitary controls apply to these varieties just as they do to traditional varieties.

EPA's Role in Assessing Pest-resistant Trees

When a tree species is intentionally modified to enhance its resistance to pests, these plants are expressing a new substance termed a plant-incorporated protectant (PIP). A PIP is defined as both the pesticidal substance and the genetic material necessary for the production of that substance. A PIP expressed in this tree must be registered with the Environmental Protection Agency (EPA) before the tree can be grown commercially. Under the requirements of the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA), EPA must determine that use of the PIP does not present an unreasonable adverse effect to the environment, taking into account the economic, social and environmental costs and benefits of that use. If the tree also has dietary uses (e.g., walnut, pinyon pine), EPA must also make a finding that there is a reasonable certainty that no harm will result from the aggregate exposure to that PIP. It is important to realize that plants modified to be resistant to a herbicide are not considered to express a PIP, but rather may have a new use for the herbicide. EPA may have to consider the risks associated with the new exposures to that herbicide's residues, but not the herbicide resistant plant itself.

EPA must examine the use of the PIP for its environmental safety in that tree species. To do this EPA makes use of the detailed description of the PIP as expressed in the plant provided as part of the USDA-APHIS review. In addition EPA reviews data generated specifically to address potential environmental effects and their associated risks. The environmental safety examination is based on two aspects: the fact that the PIP has been introduced to control a pest and therefore has some level of toxicity to a pest species, and the potentially new exposures provided by the PIP's expression in the modified plant. The toxicity examination for species other than the target pest is similar to that utilized for microbial pesticides. In addition to the direct toxicity issue, there is the consideration of both the biological and chemical fate of the pesticidal substance of the PIP. The chemical fate is the off-site movement and environmental persistence of the PIP. This would include the potential for long-term exposure in the soil and possible effects to sensitive non-target species if exposure to significant amounts of PIP expressing pollen were possible. The biological fate is the movement of the PIP gene into related plant species and potential for PIP expression in outside its intended plant host.

In addition to the risks and benefits of PIPs, EPA has also been involved in examining the risks of wide-scale use of PIPs selecting for resistance in targeted pest populations. EPA believes that many of the PIPs expressing *Bacillus thuringiensis* toxins provide a safer means of controlling insect pests. Therefore, it has been determined to be in the public interest to insure the long-term efficacy of these PIP products, as well as protecting the usefulness of pesticides based on *Bacillus thuringiensis* bacterium as an alternative to some of the more toxic chemical alternatives. Many workshops, public meetings, and SAPs have been devoted to the topic of insect resistance management, and EPA continues to be actively involved in insuring responsible use of this pest-control technology.

As is true for the development of any risk assessment guidelines, EPA has consulted with scientific experts in public meetings called Scientific Advisory Panels (SAP) to receive input on EPA's approach for assessing the environmental safety of PIPs. For a discussion of the data necessary for an environmental assessment, please visit the following website summarizing the results of recent SAPs:

www.epa.gov/scipoly/sap/index.htm

The website is organized by the date of the SAP so the following dates and subject matter serve as handy references for these reports:

February 1998—Insect Resistance Management

December 8, 1999—Product Characterization and Non-Target Effects

October 18-20, 2000—Re-Evaluation of PIPs Expresssing *Bacillus thuringiensis* Toxin

February 29, 2000—Cry9C and other Non-Digestible Proteins

June 7, 2000—Protein Toxicity Assessment

November 28, 2000—StarLink Dietary Exposure Assessment

July 17-18, 2001—CDC/FDA Analysis of StarLink Corn and Refined Dietary Exposure Assessment.

In addition, the website for EPA's Biopesticides and Pollution Division in the Office of Pesticide Programs provides up to date information on registered PIPs as well as any recent scientific or regulatory information that is cogent to PIPs. The website is also a good source on microbial and biochemical pesticides that are available for use:

www.epa.gov/pesticides/biopesticides

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International Regulation and Public Acceptance of GM Trees: Demanding a New Approach to Risk Evaluation

Sue Mayer

ABSTRACT

Establishing agreement about the environmental safety of releasing GM (genetically modified) trees to the environment will pose more challenges than for GM crops. The data considered necessary to determine genetic stability, the extent and rate of gene flow, persistence, and invasiveness of a GM food crop typically involves experiments lasting over several generations conducted under different environmental conditions. The characteristics that make trees so attractive to genetic engineers, namely their long generation times and slow growth, mean that collecting similar data about their environmental performance will require much long periods if it is to match that considered acceptable for GM crops. However, having to conduct ecological research over many years would compromise the economic viability of GM trees and conflict with the claimed benefits of speeding up tree domestication and improvement.

Reconciling these issues in a manner that commands public confidence will be a particular challenge for the regulation of GM trees. Judgements will have to be made much more explicitly, given the lack of data, revealing the inevitably subjective nature of risk assessment. Even more demandingly, the approach that is taken will either have to satisfy or be sensitive to different social, economic, and regulatory regimes in different countries to avoid acrimonious trade disputes.

Research on public attitudes to GM crops in Europe and the United States indicates that there is little confidence in the institutions dealing with safety and that public concerns are not captured by the present framing of the regulatory system. Therefore, new approaches that combine deliberative methods involving the public in defining criteria and their relative importance with expert knowledge will be required. In addition, examining different options across a range of different criteria—physical, social, economic, and ethical—will also be needed, as claims of safety will be more difficult to sustain. In this situation, rather than giving the false illusion that science can determine whether GM trees are safe or dangerous, science contributes and is necessary for decision making, but does not form a sufficient basis alone.

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Trees are long lived, large, and have long reproductive cycles. These char acteristics have contributed to their relative lack of domestication and 'improvement' through conventional breeding techniques. In contrast to, say, maize or rice where one, two, or more (with judicious use of both hemispheres) generations can be obtained in a single year, even the most rapidly growing trees take at least four or five years and often much longer to produce the next generation. However, genetic engineering brings the prospect of speeding up the domestication of trees to fit with 21st-century forestry demand for more efficient pulp and paper production. Speed, uniformity, and ease of processing and management are the driving forces behind tree breeding for this sector (Tzfira et al. 1998; Merkle and Dean 2000).

In parallel with excitement about the potential to use genetic modification (GM) comes concern about its environmental, social, economic, and political implications. Exploitation of GM trees is linked with 'intensive, short-rotation (e.g., 3–25 years) plantations' (Strauss et al. 1999), which raises questions about environmental sustainability, equity, and aesthetics (Sampson and Lohman 2000). In addition, gene movement from GM trees to wild relatives or the establishment of GM trees outside a plantation is possible, perhaps inevitable, as is considered to be the case for GM food crops (Moyes and Dale 1999). Because even those trees grown in plantations, such as eucalyptus and aspen, are relatively undomesticated, related native trees—which they can cross fertilize—often surround them. Tree pollen and seed can travel long distances and some trees can spread widely via suckers, so if GM trees became more invasive they could spread widely. Furthermore, because GM trees are being developed for a particular type of forestry, their development (or not) will also have economic, social, and political implications.

These far-reaching questions about environmental safety will be extremely difficult to answer. How will the regulatory system cope with the competing demands of the industry to capitalize on the potential for speed, with the natural constraints of the biological cycles of trees and increasing public concern about the safety of GM organisms? This paper examines the debate over the safety of GM trees and its social and political shaping, and argues that lessons from the GM debate in Europe show that a conventional risk-assessment approach will not succeed in reconciling these fundamental tensions. Unless a more comprehensive and inclusive approach to assessing the future of GM trees is adopted, polarized debate and conflict will be the outcome.

VALUE JUDGEMENTS IN RISK ASSESSMENT OF GMOs

The conventional approach to risk assessment of GM organisms focuses on the genetically modified trait and how it affects the phenotype of the organism. In the United States, the claim is that the regulatory risk assessment of a GM organism does not consider the process of genetic modification, but rather looks at the product. In Europe, in contrast, the process of genetic modification is the trigger for regulation. However, a comparison of the data requirements for assessment shows little difference with the process of genetic modification being included (seen in, for example, evaluation of the stability of the transferred gene(s)) on both sides of the Atlantic. The claimed differences are more to do with the political demands of the industry in the United States, that gene modification be constructed as being no different than conventional breeding, and the different way in which it is viewed in Europe (Mayer 2001).

As well as the characterization of the regulatory process, it is well recognized that risk assessments of GMOs and other technologies involve value judgements in deciding what the relevant criteria are (the framing of the risk assessment), their relative importance, and deciding upon the acceptability of risks given the inevitable scientific uncertainty that exists (Stirling 1998; National Research Council 1996). These value judgements may vary according to the social, political, and cultural context in which they are made. For example, until the recent debate about whether Bt toxin in GM maize can affect monarch butterflies, regulatory concerns and conflict in the United States focused on whether resistance would emerge in target organisms, compromising future use of Bt as an insecticide, and strategies to avoid this. In Europe, the emphasis in the debate about environmental impacts of GM Bt maize has been on the potential for tri-trophic effects on non-target species (Levidow and Carr 2000). Even inside the European Union, there have been disputes between Member States over the boundaries of regulation, causality, and acceptability (Levidow et al. 1997), which, with the changing political situation in Europe, have led to the revision of the Directive covering the environmental safety of releasing GMOs (2001/18/EC).

Whilst value judgements may be inevitable in making assessments about the desirability or otherwise of a particular course of action, problems may arise when the values and judgements of those taking the decision do not coincide with those held by the public. In the UK, there is evidence of a dislocation between public attitudes to GM crops and foods and those of the Government and its advisors. This mismatch extends to the scope and framing of regulations and policy and is thought to underlie the present bitter controversy about GM crops (Grove-White et al. 1997). The problems surrounding GM crops in Europe are often put down to a post-BSE (mad cow) atmosphere of lack of trust in institutions. This lack of trust in institutions managing safety in Europe is related to their (in)ability to deal with complex situations bringing together the nature of the risks, their irreversibility, and their potential for surprises, with whether there is a need for the product and who bears the risk. All of these factors have combined to bring the call for a choice about whether to eat GM foods or not. In the United States, the apparent lack of vociferous public rejection of GM foods is characterized as there being more confidence in technological developments in the United States compared to Europe (e.g., Dale 1999). However, recent research shows that concerns about GM foods are increasing in the United States, and, as in Europe, it is the regulatory process that is being questioned (Horning Priest 2000).

SHAPING THE REGULATION OF GM TREES

How well will the evolving regulation of GM trees learn from the problems encountered during the introduction of GM crops and foods? One influential body, the International Union of Forestry Research Organisations (IUFRO) Working Party on Molecular Biology of Forest Trees, adopted a position statement in September 1999 that laid out their vision of the future of GM trees and their regulation (for the full text, see http://fsl.orst.edu/tgerc/iufro_posstatm.htm). Prefaced by an explanation of a “position statement”, it states that it comes from “a society of professionals who know the scientific aspects of an area of technology controversy in depth”, thereby positioning the authors as authoritative by using the social status of science. However, as the following extract from the conclusion shows, the statement not only moves outside the expertise of tree molecular biologists, but ventures into the political domain in its efforts to shape the scope of risk evaluation and how uncertainties should be viewed:

> Tree plantations are expected to continue to expand as a result of increasing demand for their many renewable products, their importance to mitigation of greenhouse gases, and the environmental protection afforded to large areas of native forest. It is therefore important that rates of plantation productivity be made as high as possible within the context of good environmental stewardship. Transgenic technology, wisely used, promises significant economic and environmental benefits.
>
> It is critical that regulatory and certification systems have a strong scientific base that focuses on specific transgenic traits and their deployment, and that the demands of compliance are reasonable in light of the credible risks and benefits expected. These systems should also attempt to minimize the burdens required for conduct of field trials while mandating research on significant environmental impacts expected. Such systems would foster investment in biotechnology by industry, lead to an expansion of research on benefits and risks, and help to instill confidence in the public that environmental integrity is being safeguarded.

An ideological commitment to GM trees and intensive plantation approaches to forestry is seen in the first paragraph calling, among other things, on the highly political and scientifically questionable justification of mitigation of greenhouse gases. Science is then enlisted in the second paragraph to restrict the terms of regulatory controls as it has been elsewhere (e.g., James et al. 1998), with the potential benefits of GM trees being used as a justification for a narrow framing of the risk assessment. As with the GM crops debate (Levidow and Carr 2000), a scientific base (or ‘sound science’) is being used as an ideology to stifle debate and to give control of determining what are the credible risks and benefits to a certain interest group. Here a community is acting politically to further its own interests, whilst making claims to be ‘scientifically’ justified.

There are plenty of questions to ask about whether a focus on specific trait(s) is a sufficient to basis upon which to address environmental concerns about GM trees. It clearly precludes any broader assessment of forestry and whether the intensification heralded by GM is to be welcomed. Furthermore, the indirect impacts of GM trees include changes to forestry practices which demand attention. For example, the introduction of herbicide-tolerant crops would change the pattern of herbicide use with knock on implications for biodiversity. Similarly, Bt-toxin-based approaches to insect control would alter exposure to insecticides. In contrast to food crop farming, insecticide use in forestry is rather restricted because of the scale of forests and costs involved. However, exposure to Bt continuously over many years could have serious impacts on insect populations that will be extremely difficult to predict. In Europe, the relevance of indirect impacts on biodiversity has been recognized, and experiments are beginning to consider them (Firbank et al. 1999), but a trait-based approach to risk tends to marginalize these indirect impacts and preclude research.

In addition, there is a question about whether safeguards put in place will be effective or practicable. The Starlink contamination of maize for human consumption in the United States, and the nearly one-third of U.S. farmers using GM Bt crops who may have failed to fully comply with refuge strategies to prevent the development of Bt resistant insect populations (Coghlan 2001), shows how important this dimension can be in determining whether a hazard is realized or not. Again, however, such issues are marginalized in a risk-assessment system that focuses on the transgenic trait.

And why should the burdens on field trials be minimized? Asking appropriate questions that are rigorous and justifiable is the most important issue, and proper scrutiny of this is needed. Easier, less-regulated experiments do not mean the best data will be produced upon which to base a risk evaluation. It may simply be that numbers of trials are used as a spurious claim of safety, as they have been with GM crops, even though most small-scale experimental releases do not investigate environmental impacts (Mellon and Rissler 1995). The unknowns and uncertainties in the ecological impacts of GM trees are enormous, and any effects are likely to remain undetected for many years and be irreversible. Even if male-sterile trees are produced, how confident can we be that the transformation will be stable? Studies of non-GM hybrid trees may show that although gene transfer can take place over long distances, offspring do not compete well against native trees; how confident can we be that the same will hold true for the traits introduced through genetic modification and that there have been no unexpected changes as a result of the gene introduction? It is clear that the level of confidence that is expected in order to make judgements about GM crops safety (which itself is contested as inadequate, e.g., Melon and Rissler 1995; Rissler and Mellon 1996) simply will not be available for GM trees. The only reason for accepting a lower standard can be if there has been a policy commitment to GM trees and plantation forestry, and a belief that the benefits will outweigh any risks.

Therefore, if the United States follows the advice of the IUFRO Working Party on Molecular Biology of Forest Trees. it will politically restrict the framework of the assessment and lower the demands for data to verify assumptions, in the interests of the industry and tree molecular biologists. If these value judgements and policy commitments are widely shared in society, then it will be an approach that carries public confidence; if not, conflict is the more likely outcome. Even though the new European approach takes account of indirect effects, socioeconomic impacts are excluded because of a long-standing policy commitment to biotechnology as a driver of industrial competitiveness, and thus, European decisions may also fall foul of public opinion if this is not agreed for GM trees (Mayer and Stirling 2001).

FINDING MORE ROBUST APPROACHES TO RISK EVALUATION

The main justification for intensifying forestry practices via GM is to meet the increasing demand for pulp and paper and the need to make its production more efficient (Tzfira et al 1998; Sederoff 1999). However, this begs the question as to whether this demand should be met or needs to be met. If demand can be reduced, this might obviate the demand for GM trees. In other words, GM trees and intensification of forestry are unlikely to be the only solution to the problem of pulp and paper supply. Similarly, if we were to accept as non-contentious the aims of mitigating greenhouse gases and protecting native forests, would GM trees be the only or best solution?

A problem of conventional risk assessment is that it never addresses questions like these openly. Only one option is compared to an ill-defined yardstick of harm (usually conventional practice) and a single answer is given—safe or dangerous—which conceals a host of scientific uncertainties, ignorance, and value judgements. Conventional risk assessment also relies only on a narrow construction of expert knowledge and the moral, social, political, and economic values the chosen experts bring to the judgements they make. The public is effectively excluded from the process, as is expertise from outside the officially mandated boundaries.

However, there are alternatives that can bring a more robust approach to risk evaluation by examining the relative performance of options across a variety of different criteria. One of these approaches is multi-criteria mapping, which has been used to examine options for the growing of GM oilseed by 12 participants with very different perspectives (Stirling and Mayer 2000; Stirling and Mayer, in press). The options included three with varying controls on GM crop production, and three that excluded GM: conventional, low input, and organic systems. In this study, the outcome was driven by the participants who chose the criteria for evaluation, scored the performance of each option under each criterion (including an estimate of uncertainty), and attributed weightings to the criteria. Criteria chosen ranged from those concerning food and environmental safety, to social, economic, and agronomic issues.

The outcome was not a single answer, but a map of the debate in the form of relative rankings of the performance of the options from a range of perspectives, which is then available as a heuristic device for decision makers. It illuminated areas of agreement, such as the finding that an organic system performed better than any other option in environmental terms, whatever the starting position of the participant. Voluntary controls on GM crops and foods were also seen as generally less desirable than regulation for a variety of different reasons, including that they are more likely to be followed and that consumer confidence will be increased, thus improving market potential. Key areas of disagreement, such as the relative human health effects of foods produced under different systems and the rigor of regulatory controls were also highlighted, proving opportunities for further research that might resolve the disputes. What was quite clear was that the framing of the assessment and the judgements made in scoring—which criteria were included and excluded and the factors influencing scoring—drove the final outcome. Altering the weighting placed on the criteria made relatively little difference to the outcome, highlighting how value laden and important framing and scoring are.

Whilst this use of multi-criteria mapping showed the potential for comparing different options, it relied on people who would widely be regarded as 'experts'. Therefore, to be robust it must be brought together with public input to inform the choice of criteria, weightings, and options. Without this, the approach could suffer from a dislocation from public values as conventional approaches do. However, the exercise showed that such an approach was practical and could be used productively in the early stages of technology assessment to assist in determining policy and how judgements should be made, if a case-by-case approach is subsequently adopted.

DISCUSSION

No GM trees are currently in commercial production. Investment in long-term research in forestry is small compared with crop production (Robinson 1999), and trees have proved more technologically demanding to manipulate than other plants (Tzfira et al. 1998). However, there is considerable interest in promoting their use, and controversy has already surrounded trials with GM trees in both the United States and Europe. In deciding upon experimental trials and commercialization, regulators will inevitably have to make their underlying political, social, and economic justifications more explicit than for GM food crops, because the scientific uncertainties and unknowns are so great and physical containment impossible. A claim to risk assessments being scientifically driven alone will not be effective at concealing the value judgements.

The imposition of GM trees in forestry and the denial of the importance or relevance of the wider dimensions of risk, including socioeconomic impacts, is likely to fuel controversy and engender a polarized and non-productive debate. Past experiences with GM crops have demonstrated that such conflict will not be contained inside national boundaries. Given the cultural, social, and symbolic importance of forests, there is likely to be a fierce battle fought at all levels, from the local to the intergovernmental, unless steps are taken to reevaluate the approach being taken to risk assessment. New methods will be needed that allow for public input and thus have the potential for promoting more socially resilient decision making, but there will have to be openness to different outcomes by all sides.

Whilst science will be necessary in informing decisions, it is not a sufficient basis upon which to do so (National Research Council 1996). The EU-US Biotechnology Consultative Forum (2000) recognized the legitimacy of the increasing demands to democratize the decision-making processes around GM foods, and this lesson should be taken on board by the GM tree community.

Multi-criteria mapping is not the only approach that could be used to evaluate the use of a new technology in a particular setting. There are many participatory techniques, such as citizen juries and consensus conferences, which could also be applied, and a combination of approaches may prove the best solution. It may seem that techniques like these will be cumbersome and will delay technological progress. However, the intense controversy surrounding GM crops and the damage that has been done to an industry and to confidence in public institutions demonstrates that shortcuts may not, in the long run, be a productive approach. If the trajectory of GM crop development and its regulation had been allowed to have greater public input in the 1980s and early 1990s, the situation now might be very different.

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FOREST SCIENCE

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Transgenic Trees: Where are We Now?

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ABSTRACT

Numerous field tests throughout the world clearly demonstrate that it is possible to genetically engineer diverse tree species. Despite these results, the main challenge with trees continues to be the development of efficient transformation systems for the most desired genotypes. In this regard, it is not transformation *per se* that is limiting, but rather the tissue culture system needed to regenerate whole trees from single cells containing the inserted genes (transgenes). Although more research is needed, results from field tests have been invaluable for improving our understanding of how inserted genes will be expressed in long-lived perennials.

Available evidence suggests that the issues associated with transgene expression in trees will be the same as those observed in agronomic crops. To date we have seen that 1) transgene expression levels vary between transformation events/lines, species, transgenes, and traits being modified; 2) targeted, tissue-specific expression of transgenes is possible; 3) transformation events that give consistent levels of gene expression in primary transformants are the rule, not the exception; and 4) it is possible to find whatever is being sought, whether it be gene silencing or commercially useful expression. These trends suggest that although additional work is needed in the area of temporal and developmental regulation, stable, long-term expression of transgenes in trees is readily achievable.

Similarly, somaclonal variation does not appear to be a widespread phenomenon when regenerating transgenic trees. The use of embryogenesis helps reduce the incidence of this with gymnosperms, and with available practices and care in tissue culture, somaclonal variation is not a limitation with angiosperms.

Another factor that will play a role in the use of genetically modified trees is the possibility of undesirable levels of transgene spread. Environmental risks associated with transgene movement are specific to the gene(s) being inserted, the tree species, and the environment within which the transgenic tree is planted. Clearly, pollen and seed have the greatest potential to facilitate transgene movement. Whether this occurs depends on the reproductive biology of the species in question, the management scheme being used, and the proximity of transgenic trees to sexually compatible relatives. Although cultural and deployment strategies could be used in some locations to minimize the risk of transgene spread, another approach is to link genes that inhibit floral development with the transgene of interest. Several labs are using this approach to develop methods for transgene containment.

In many respects, the process of stably integrating a piece of DNA into the nuclear genome is similar in both trees and agricultural crops. There are numerous examples of success with transformation in both systems. The first commercial release of a transgenic tree occurred several years ago in Hawaii with papaya. This release, the first and only commercial release, to our knowledge, of a long-lived perennial crop, not only demonstrates the efficacy of this approach for the genetic improvement of trees, but also serves to answer many of the questions regarding the stability of transgene expression in trees. As with other agricultural crops, papaya growers have enthusiastically embraced biotechnology, as evidenced by the rapid adoption rates and continued satisfaction with the product. Although numerous trans-genic crops have been commercialized (see: http://www.aphis.usda.gov/biotech/), papaya represents the only commercial release of a transgenic perennial.

At present there is neither a shortage of genes nor methods for incorporating them into trees, and the genes that are inserted are expressed adequately. What we currently lack is the ability to coax individual cells from commercially important genotypes to grow into whole plants. This is not an issue with transgenics *per se*, but is instead a tissue culture problem. It is also not a problem that is unique to trees, as it exists with agricultural crops as well.

Why then are there far more commercial releases in agricultural crops? Economics play a large role, but fundamental biology also plays a role. In annual agricultural crops, tissue culture systems need to only be developed for a very few breeding lines and then the transgene can be rapidly incorporated into elite lines through traditional breeding. For example, in maize, even though hundreds of different transgenic varieties are available and transgenics account for 26% of the acreage planted in 2001, all of these varieties were derived from only five transgenic events in as few as two breeding lines.

The ability to introgress a transgene through breeding is key to the very rapid development of engineered maize varieties. A single transformation event can theoretically be introgressed from a breeding line into an elite line in nine generations, or in a few as three years. This enables the various maize cultivars, each specifically adapted to different locations or environments, to all have the same reliable expression of a trait imparted by a single insertion event. In addition, the resulting varieties can be readily amplified for rapid deployment. Equally important is that due to the ease with which a transgene can be introgressed, tissue culture and transformation systems are not needed for each commercial variety of maize.

This is in stark contrast to trees, where introgressing a transgene into superior genotypes through breeding is not currently possible. Even if the long regeneration cycle in trees could be overcome, inbred lines or breeding lines required for such an introgression program have not been developed. Right now, the only option for trees is to develop robust transformation systems that are adaptable to the many genotypes used in clonal plantation forestry.

However, tissue culture systems for all commercially important genotypes in forestry are not available at present. Each genotype requires a slightly different set of conditions to induce individual cells, containing the inserted DNA, to differentiate into whole plants. Our ability to identify the specialized conditions needed for individual genotypes is currently a major limitation.

Generalities in the literature can, and have, led researchers to assume that numerous tree species can be transformed. It should be emphasized, however, that in many cases a single genotype of a species has been transformed. Poplar, which has been touted as the “model tree” for molecular biology studies, provides a good example. Indeed, it has a small genome and, by all indications in the literature, it can be transformed at a high frequency. Yet a careful look at the reports on field trials of transgenic poplars reveals that a majority of lines described have been produced in just a handful of genotypes. Further, only a few if any, of these genotypes are grown commercially. Thus, the manipulation of commercially important genotypes in tissue culture remains an obstacle to gaining the full economic benefit from transgenics in forestry.

Despite this limitation, there are over 100 reports of trees being transformed with valuable traits, including herbicide and insect resistance (Fillatti et al. 1987; De Block 1990; McCown et al. 1991; Brasileiro et al. 1992; Devillard et al. 1992; Chupeau et al. 1994; Donahue et al. 1994; Wang et al. 1996; Cornu et al. 1996; Leplé et al. 1995; Heuchelin et al. 1997; Meilan et al. 2000); modification of lignin (Van Doorsselaere et al. 1995; Baucher et al. 1996; Pilate et al. 1997; Hawkins et al. 1997; Hu et al. 1997; Franke et al. 2000; Li et al. 2001); glutathione metabolism (Foyer et al. 1995; Strohm et al. 1995); modification of cellulose (Shani et al. 2001); bioremediation (Rugh et al. 1998; Gordon et al. 2001) and altered hormone biosynthesis (Eriksson et al. 2000). In this paper, we discuss some of the challenges, both perceived and real, for using transgenes in long-lived perennial crops.

GENE EXPRESSION

A question continually asked regarding transgene expression in long-lived perennial crops, such as trees, is how can one be sure that transgenes will continue to be expressed over the years or decades required for a rotation? To answer this question, one must look at the data available from transgenic crops, both annual and perennial.

It is important to start any discussion on the expression of transgenes with the realization that variation and instability in transgene expression does exist, just as variation in gene expression exists in breeding. Indeed, if variation in gene expression did not exist, breeding programs would be severely hampered. Further, just as in breeding, if one looks hard enough, it is possible to find virtually any pattern of gene expression desired, from suppression to high-level expression. Fortunately, in both transgenics and breeding, the selection for stable gene expression is a frequent event and is very reliable. If this were not true, there would no commercial transgenic crops and the industry would not have advanced to its present state.

Historically, primary selections were done based on the desired level or location of transgene expression. Recently there has been a shift toward selecting for simpler insertion patterns and agricultural crops are now selected for single events. This change has been made mainly to satisfy regulatory requirements for complete molecular characterization, including sequence information, for each insert and its flanking genomic DNA (i.e., characterizing a single site requires less effort than doing multiple sites).

It should also be noted that the authors have found no reproducible evidence to support the dogma that there is increased variation in expression patterns with multiple insertion sites, and we do not want to imply that this helps explain the rationale for selecting simple insertions events. In discussions with colleagues working in agricultural biotechnology, it has been repeatedly confirmed that there is little support for the notion that a greater number of insertions translates into increased variation in transgene expression. Rather, the available data suggest that the desired level of transgene expression occurs frequently enough to obviate the need to use insert complexity as the primary criterion for selecting transgenic events.

The foregoing discussion addresses variation in transgene expression, but the most important question, asked in the first paragraph of this section, concerns the stability of transgene expression over time in long-lived crops. As with expression level, it is easy to speculate that biotechnology companies select for simple insert patterns in hopes of achieving more stable expression. Again, we find no reliable documentation to support the doctrine that simple transgene insertion patterns lead to more or less stable expression.

It is of paramount importance to have transgenes expressed in the expected way throughout the life of the tree. There is abundant evidence that transgenes are expressed faithfully over time. In agricultural crops, there is no question that such stability in transgene expression exists; markets would not have increased if transgene expression levels could not be trusted. In any case, all that is important is to have the transgene expressed sufficiently to impart the desired trait (e.g., herbicide tolerance, or insect resistance, etc.) at useful levels. Presently, we do not fully understand how transgene expression levels vary over time or in different environments.

There is evidence that transgene expression is very stable in trees over time. In an early study, Ellis et al. (unpublished) measured the expression of *GUS* (a visual reporter gene) in field-grown transgenic poplar and spruce over a three-year period. In this study, they observed that variation in expression levels between individuals within a single line were greater in the field than in tissue culture. They speculated that similar trends in gene expression would also be noted if one were to measure a native gene, and that environmental factors affecting gene expression were minor in tissue culture and far greater in a field setting. In addition to this within-line variation, differences *between* lines were significant and these differences were consistent throughout the year. Of greater importance was the observation that during the three-year study, the level of *GUS* expression was not significantly different ($P < 0.05$) from year to year for ~85% of the 15 yearly sample dates.

In another aspect of this same study, transgene expression was measured over several years in poplars that contained

GUS under the control of the promoter from a wound-inducible gene, *PINII*. *GUS* expression was found to be consistent over the two-year field study. Further, the level of *GUS* expression was faithfully induced in a very strict developmental pattern throughout both years. These data demonstrate that transgenes need not be expressed continuously in order to be reliably expressed in trees at specific developmental stages. This issue is crucial in the later discussion on the disruption of reproductive structures in trees.

Meilan et al. (2001a) assessed the stability of transgene expression in 40 transgenic lines (i.e., independent events) of hybrid cottonwood (*Populus trichocarpa* x *P. deltoides*) grown at three field sites during four years of field trials. All lines were transformed with a binary vector that included two genes conferring tolerance to glyphosate (*GOX* and *CP4*), a gene encoding resistance to the antibiotic kanamycin (*NPTIl*), and *GUS*. *Agrobacterium tumefaciens* was used for transformation; callogenesis and organogenesis occurred under kanamycin selection. To test the stability of transgene expression, they repeatedly applied herbicide to all lines after outplanting, challenging ramets from previously untreated lines during their fourth season of vegetative growth. They used maintenance of herbicide tolerance and *GUS* expression as indicators of transgene stability. Their data show that all lines that were highly tolerant in year one continued to be highly tolerant in year four.

In what is perhaps the most ambitious study done to date with transgenic trees, Pilate et al. (2001) examined transgene expression in field-grown transgenic poplar for a decade. In this study, they also observed very stable and dependable *GUS* expression from year to year. More importantly, they found no evidence for transgene rearrangements, multiplication, loss, or other modifications. These data are the strongest indication that transgene expression is stable in long-lived perennial crops such as forest trees.

Han et al. (1997) evaluated the use of a matrix-attachment region (MAR) fragments derived from a tobacco gene for increasing the frequency of *Agrobacterium*-mediated transformation. MARs are elements of DNA that can enhance and stabilize transgene expression (and Thompson 1996). A binary vector that carried the *GUS* reporter gene containing an intron and an *NPTII* gene was modified to contain flanking MAR elements within the T-DNA borders. The modified and MAR-containing vectors were used to transform tobacco, a readily transformable poplar clone (*P. tremula* x *P. alba*), and a recalcitrant poplar clone (*P. trichocarpa* x *P. deltoides*). MARs significantly enhanced transgene expression and transformation efficiency, but the effects varied widely in magnitude among genotypes. MARs increased *GUS* gene expression approximately 10-fold in the two hybrid poplar clones and two-fold in tobacco one month after co-cultivation with *Agrobacterium,* and increased the frequency of kanamycin-resistant poplar shoots recovery more than eight-fold. Thus, MARs hold considerable promise for use with poplar, if necessary.

Despite these encouraging results, it has been suggested that the best evidence for expression stability is maintenance through meiosis. While using primary transformants in proven elite genotypes is the current focus of transgenic trees, future breeding programs will benefit from the inclusion of transgenic traits. Therefore, the question of transgene expression in progeny is of practical significance. In the only known example of transgenic inheritance in forest trees, Pilate et al. (2001) observed the expected Mendelian segregation ratio for progeny from a line containing a single-copy insert. Moreover, the authors detected a fragment of the expected size hybridizing to a *GUS* probe in all kanamycin-resistant lines. In contrast, a line containing four inserts produced progeny containing 1, 2, 3, and 4 copies of the segregated transgene. Transgene expression level between the progeny from both transformed lines was highly variable, but this is to be expected from heterozygous offspring.

In addition to variation in the level or timing of transgene expression, there have also been numerous reports of transgene silencing. This phenomenon has been reviewed extensively (e.g., Finnegan and McElroy 1994; Stam et al. 1997; Matzke and Matzke 1998). One form of silencing occurs at the level of transcription, and usually involves methylation of promoter regions, but may also involve chromatin modification (van Blokland et al. 1997; Finnegan et al. 1998). These reports have erroneously led many to conclude that silencing is a major problem confronting genetic engineering. As mentioned in the beginning of this section, it is possible to find whatever is desired, and gene silencing is no exception.

Because it is scientifically interesting, there are many reports of transgene silencing in the literature. However, it is a rare occurrence in our hands and definitely not a problem at present with the promoters, genes, or constructs currently being tested in trees.

Pilate et al. (unpublished data) observed only one case of transgene silencing in their work. This silencing event occurred after selection but prior to any analysis of the transformed lines. Interestingly, this is similar to the only case of transgene silencing seen by Ellis et al. in poplar, where again the putative silencing event was found early in tissue culture. In both cases, 5-azacytidine had no effect on the silencing, indicating that either methylation was not involved, or that the silencing was not due to an azacytidine-reversible methylation event. These two incidents of gene silencing, while of academic interest, occurred in less than 1% of all transgenic lines analyzed.

In addition, Meilan et al. (2001b) conducted a two-year field test in which they evaluated 80 transgenic lines for genetically engineered herbicide tolerance. They observed an abrupt increase in mean herbicide damage for two of these lines from one year to the next. One possible explanation for loss of tolerance is transgene silencing. A recent report described how cold-induced dormancy led to elevated methylation, which in turn, led to partial transgene silencing (Callahan et al. 2000). The possibility of year-to-year variation in transgene expression highlights the importance of conducting multi-year trials. All 80 lines were vegetatively propagated and have been planted on another site to monitor their growth and herbicide tolerance for several years.

Contrary to what we have collectively seen in our work, there is recent evidence for a high level of co- or sense-suppression in poplar with constructs used to over-express genes involved in lignin biosynthesis. Examples of genes that have been co-suppressed include *COMT, CAD, 4CL,* and *C4H* (Jouanin et al. 2001; Tsai et al. 2001). It is not known whether this suppression is the result of using homologous genes or will become more frequent as more tree genes are used. It is feasible that this silencing phenomenon could be unique to the lignin biosynthetic pathway. Clearly, it will be interesting to see if silencing is a function of the biochemical pathway being manipulated or the source of the genes used to manipulate the pathway or both.

SOMACLONAL VARIATION

Much like transgene silencing, somaclonal variation, a stable genetic change in somatic cells of a plant, does occur, but can be minimized or avoided with careful control over cultural conditions. Somaclonal variation tends to more common with unstable genomes, such as with tetraploids, although we know of no tetraploid trees currently in commercial use. However, with the increased use of hybrids or triploids, the occurrence of somaclonal variation may increase. Despite this, it should be noted that, to date, the authors have rarely seen evidence for somaclonal variation in any of their transgenic poplars.

In one study on the induction of somaclonal variation in poplar, Ostry et al. (1994) started with the same mother plant, and compared regenerated shoots derived from embryogenic cell suspensions, protoplasts, leaf micro-cross sections, callus, and shoot or root cultures. Somaclonal variation was scored using morphological characters and increased resistance to Septoria, based on a leaf disc assay. Morphological variants were noted in adventitious shoots regenerated from roots, callus, and protoplasts, with shoots from stem callus yielding the highest level of Septoria-resistant plants. These data confirm earlier work suggesting that the longer cells are maintained in an unorganized culture, the greater the likelihood of somaclonal variation occurring (Larkin and Scowcroft 1981; Bajaj 1990; Deverno 1995).

In a related study (Serres and McCown, unpublished), plants from approximately 400 colonies derived from individual protoplasts were regenerated and grown *ex vitro*. After 10 weeks in a greenhouse, the plants were scored for 17 different parameters ranging from leaf size and shape to internode length. In all, nearly 50% of the regenerated plants had some morphological differences from the control, with the greatest number of variants being in height, leaf length/width ratio, stem diameter, and number of nodes. These changes were stable in the greenhouse and most remained throughout the first season when the plants were grown in the field. The plants were allowed to over-winter out-of-doors and were scored again the following spring, after leaf flush. In the second year, only three lines continued to display abnormalities; two lines showed sectoring in the leaves, perhaps caused by a transposition event, and the remaining line had the appearance of a diploid (Serres et al. 1991). Clearly the majority of the variations were epigenetic changes and not true genetic or somaclonal changes.

Meilan et al. (unpublished) have produced >3,200 independent transgenic lines in 16 different poplar genotypes (14 of cottonwood, sections Tacamahaca and Aigeiros, and two of aspen, section Populus or Leuce). They field-tested 557 of those lines, and have grown most of the remainder in the greenhouse for extended periods. Of the total, they have observed morphological abnormalities that were not induced by transgene expression in only three lines (0.1%). None of these variant lines were in hybrid aspen. The three lines in which they did observe putative somaclonal variants were all hybrid cottonwoods, whose transformation protocol requires that they that spend nearly twice as long in an undifferentiated state as do the aspens (Han et al. 2000).

These studies are consistent with the view that the avoidance of an unorganized callus stage, and the minimized use of hormones to maintain or regenerate shoots are important measures for reducing somaclonal variation. It should be noted, however, that even in the case of protoplasts, where thiadiazuron and both an auxin and a cytokinin were used for regeneration, less than 2% of the regenerated shoots exhibited stable and confirmed somaclonal variation.

We maintain that with careful attention to culture conditions, somaclonal variation will not be a problem with transgenic plants.

TRANSGENE CONTAINMENT

It must be understood from the outset that no one can guarantee absolute sterility in trees with the tools that are currently available. However, from a scientific, or even a purely risk assessment standpoint, flowering control may not always be needed before transgenic trees can or should be grown commercially. There also may be cases where it would be desirable to incorporate transgenes into a conventional breeding system. Thus, the need for sterility will depend on the trait; the environment within which the transgenics will be grown; the species; and various social, political, and ethical considerations. Each case must be considered individually.

That being said, virtually everyone who is working with transgenic trees for fiber production is also interested in engineered sterility. Controlling the potential for transgene spread will facilitate commercial release and may help to moderate the perceived negative environmental impacts of genetically engineered trees. It is also likely that the trees engineered to be reproductively sterile will grow faster and prevent unwanted genetic pollution.

CONTROL OF REPRODUCTIVE STRUCTURES

Being able to genetically engineer reproductive sterility in trees is desirable for several reasons (Strauss et al. 1995; Brunner et al. 1998; Skinner et al. 2000). First, it will enable the development of trees that are incapable of producing sexual propagules. This would limit gene flow into the wild, helping to mitigate ecological concerns over establishment of transgenic plantations. Second, it will likely prevent the growth reduction associated with the onset of maturation (Eis et al. 1965, Tappeiner 1969; Teich 1975). Third, it could eliminate the production of pollen and other nuisance reproductive structures.

One common way to engineer sterility is to ablate cells by expressing a deleterious gene in a tissue-specific fashion (Brunner et al. 1998). Floral tissue-specific promoters are fused to one of a variety of cytotoxin genes that lead to rapid and early death of the tissues within which the gene product is expressed (Skinner et al. 2000). One of the more popular ways to engineer sterility in herbaceous plants employs an RNAse gene that, although isolated from a bacterium, encodes an enzyme that is common in plants and animals (Mariani et al. 1990).

A second way to genetically engineer flowering control is through the use of dominant negative mutations (DNMs). DNMs suppress the function of a gene at the protein level by overexpression of a mutant version of a protein (Espeseth et al. 1993). Inhibition is thought to occur by a variety of means, including formation of an inactive heterodimer, sequestration of protein cofactors, sequestration of metabolites, or stable binding to a DNA regulatory motif. The usefulness of this approach for floral control was demonstrated in

Arabidopsis with DNM versions of the *AGAMOUS* (*AG*) gene (Mizukami et al. 1996). Expression of a truncated AG protein in which the C-terminal region was deleted resulted in flowers phenotypically similar to those observed in ag mutants, suggesting that the truncated version of AG was inhibiting endogenous AG function.

A third technique to control flowering involves post-transcriptional gene silencing (PTGS). Recent studies in a variety of eukaryotic organisms have shown that double-stranded RNA is a potent inducer of PTGS. This approach to induced silencing has been termed RNA interference (RNAi) (Fire 1999; Bosher and Labouesse 2000). Recent work in plants using inverted-repeat transgenes showed that RNAi could provide a reliable means for engineering stable suppression of gene activity in plants (Waterhouse et al. 1998; Chuang and Meyerowitz 2000).

Below we briefly discuss recent progress made with one approach to flowering control in trees.

CELL ABLATION

In early attempts at utilizing cell ablation with poplar, heterologous promoters, which had shown floral-specific expression in tobacco and *Arabidopsis* (Koltunow et al. 1990; Hackett et al. 1992; Wang et al. 1993), were used to drive the expression of two cytotoxin genes, *DTA* (Greenfield et al. 1983) and barnase (Hartley et al. 1988). When introduced into transgenic poplars, these fusions resulted in decreased vegetative growth, suggesting leaky expression in non-target tissues (Meilan et al. 2001c).

Now that floral homeotic genes from poplar have been cloned and characterized (Brunner et al. 2000, Sheppard et al. 2000; Rottmann et al. 2000), work has begun on experimenting with promoters from poplar genes. The promoter from *PTD* (the *P. trichocarpa* homolog of *DEFICIENS*) appears to be the most floral-specific in its expression pattern (Sheppard et al. 2000). We have shown that *PTD* promoter directs expression of the *GUS* gene early in the development of floral organs in Arabidopsis and poplar (Figure 1). The latter was co-transformed with the *LEAFY* (*LFY*) gene from *Arabidopsis* under the control of the 35S promoter, which has been shown to induce early flowering in poplar (Weigel and Nilsson 1995). When the *PTD* promoter was used to drive the expression of a cytotoxin gene (ribosome inactivating protein, RIP), petals and stamens were ablated in Arabidopsis; petals, stamens, and carpels were absent in transgenic tobacco. PTD::*RIP* also appears to prevent flowers from forming on poplar co-transformed with 35S::*LFY* (Figure 2). Expression of PTD::*RIP* had no significant effects on growth in tobacco. Based on these results, it appears that the *PTD* promoter may be useful for engineering sterility in a variety of species.

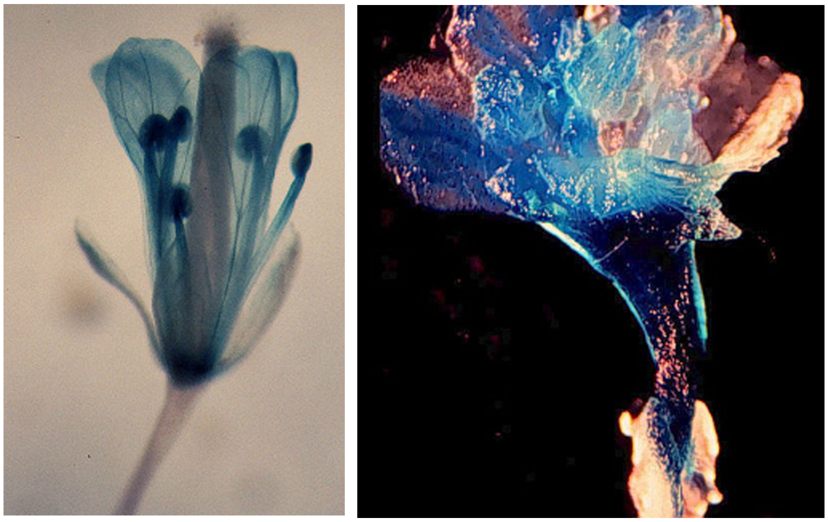

Figure 1. GUS expression under the control of the PTD promoter in Arabidopsis (A) and poplar (B) flowers.

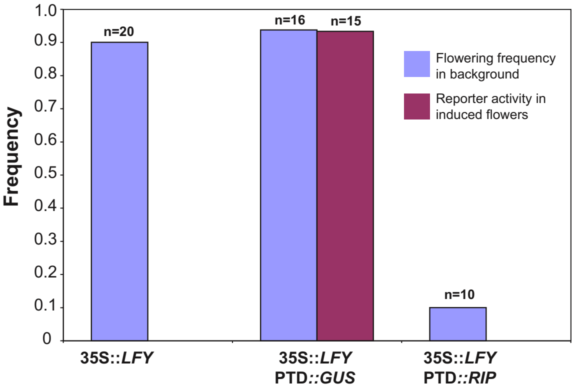

Figure 2. Flowering frequency (Freq.) of poplar transformed with 35S::LFY alone (which induces flowering) or in conjunction with a fusion between either a reporter gene (GUS) or a cytotoxin gene (RIP).

CONCLUSION

We have shown that significant amounts of data have been gathered for transgenic trees over the past several years in numerous small-scale, short-term field trials conducted in three countries and on two continents. These data show that, contrary to what our critics may believe, we can produce transgenic trees with almost no evidence of collateral genetic damage to the tree (i.e., somaclonal variation), and that inserted genes are expressed stably from year to year, after vegetative propagation, and in a variety of environments. We have also shown that it should soon be possible to genetically engineer flowering control in trees.

Finally, we recognize the need for larger-scale, long-term ecological studies in order to evaluate potential risks to the environment.

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Perspectives on Risk in Transgenic Forest Plantations in Relation to Conventional Breeding and Use of Exotic Pines and Eucalypts: Viewpoints of Practicing Breeding and Transformation Scientists

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ABSTRACT

Risk factors associated with transgenic material of exotic pines and eucalypts reflect (1) special features of pines and eucalypts as such, compared with other forest tree crops; (2) the technical and commercial risks that may be specific to transgenic crops rather than the products of conventional breeding; and (3) the mainly perceived risks of transgenic plants to the environment or human health. The features that are in varying degree specific to pines include crop lifespan (relating to both the potential magnitude of certain risks and the need for stable, long-term expression of transgenes); natural silvics (largely favoring species monocultures); soil and climatic tolerances (effectively restricting the feasible control over growing environments); wind pollination (causing problems of containment); and the associated outbreeding system. All these features may accentuate the risks associated with operational deployment of transgenic material. Comparisons between pines and eucalypts, and the implications of the main differences, are outlined. Exotic status tends to reduce some risks, but accentuate others. Among the risks, those involving crop vulnerability are seen as especially relevant, unlike many of the commonly perceived risks associated with transgenic crops. Such risks are potentially of great economic and therefore social significance. Use of transgenics may often contrast with conventional breeding, and especially evolution, in potentially skipping the typical testing of low-frequency alleles by natural selection. However, the introduction of an already tested gene into an organism may effectively mimic accelerated evolution. Field testing can help to identify and minimize various risks, but can in some cases significantly increase time required to commercialize transgenics. Spread of risk, among transformation events and transgenes used, in addition to among recipient genotypes, seems highly prudent, but regulatory protocols may create obstacles. However, strategies may need to be developed that stop the spread of transgenic material through sexual reproduction, without incurring new and significant risks. Further, the use of multiple transgenes in any recipient genotype may increase risks, from possible interactions among transgenes as well as simply summing the specific risks for individual transgenes. Risks of using transgenics must be evaluated against those of not using a technology that has the potential to greatly benefit humankind.

To begin, we define the general concept of risk, as a function (roughly speaking, a product) of the probability of a negative effect occurring and its magnitude (or seriousness). In turn, the magnitude can be viewed as roughly the product of the severity of the event and the scale on which it occurs (Burdon 1999); for instance, 100% mortality of a cultivar may be a severe event in relation to that cultivar, but not a serious one if only a few trees of it have been planted. Where the probability is unknown, the term *uncertainty* is widely used. Yet, even if the probability is of a low but uncertain value, it cannot be readily discounted if the potential magnitude is extreme. In that situation, it becomes necessary to make judgments as to just how low the probability is, and there will be cases where there are good reasons for believing that it is essentially zero. The genetic engineering debate worldwide has become characterized by confusion over the term *risk*. While there are attempts to define and quantify risk, there is growing concern that the term is used misleadingly, with a readiness to view any non-zero probability as being effectively high, and to ignore risks that arise without genetic engineering (Bazin and Lynch 1994). Further, the occurrence of an effect as such is often not clearly defined. The risk discussion is in many cases characterized by claims that a specific effect will occur, without reference to, and analysis of, the individual steps that have to happen for an effect to occur.

The result of a genetic transformation is an organism that carries a new sequence of DNA at one or more locations within the genome. If such a sequence is already present in nature in one way or another, we have something very much like the possible outcome of natural gene transfer (also termed Horizontal Gene Transfer or HGT). Although many opponents of genetic engineering regard the former as a risk and ignore the latter, no potential or perceived effect can actually be regarded as a risk without some actual analysis. A new sequence of DNA in an organism will often have an effect such as a new protein produced, if it codes for a structural gene, or simply the ‘wastage’ of a small amount of resources to replicate the new DNA. The latter type of effect can be regarded as neutral with regard to the environment or human health. In specific circumstances, the effect will be beneficial to the organism, for instance, when the new gene provides selective advantage. The effect may be negative if the new sequence of DNA reduces fitness. Also, an effect that is beneficial to the organism might be a risk for the environment. The same, however, is true for the outcome of a conventional breeding experiment, where new gene combinations may be ‘beneficial’ for some applications, but a risk for the environment. The generation of an organism with potentially unknown characteristics is a potential threat in relation to all efforts of humankind to modify existing planting stock according to their needs.

Any potential risk should have to be assessed in the context of the particular organism, and in context of the particular environment the organism is living in. While the engineered or bred product may have low risk potential in a specific environment, this may not be so in a different environment.

In any event, certain risks of crop failure can arise in plantations whether they result from conventional breeding or genetic engineering. Further, a specific new genotype produced either way must respond to the specific environment in which it is grown. The resultant of genotype and environment will finally decide the success or failure of the crop (genetically modified or not), and the potential risks.

To address our specific brief, we will first identify key features that differentiate, in connection with risk factors, exotic pine plantations from traditional crop plants and/or other forest trees, and eucalypt plantations from exotic pine plantations. In this context we will address the various categories of risk. We will then compare briefly the use of genetic transformation with the processes of both natural evolution and classical breeding, and consider horizontal gene transfer. We will follow by addressing risk profiles and risk management, before our final comments.

DISTINGUISHING FEATURES OF EXOTIC PINE CROPS

The crucial features that often distinguish pine plantations from other types of crop and other forest trees may be listed as crop lifespan (i.e., rotation age), natural silvics, soil tolerances, climatic tolerances, wind pollination, and the associated outbreeding system. Exotic status is a less consistent feature of pine plantations (given, for example, the huge areas of plantations of loblolly pine within its natural range), and one of more ambiguous significance (in respect of biotic risks that may interact with the risks of genetic transformation) (Burdon 1999). For example, an exotic crop may be growing in the absence of a disease, but if the disease arrives, and conventional breeding or transformation have accidentally (and perhaps unknowingly) increased a susceptibility that is already high in the exotic environment, the outcome could be very serious.

Crop Lifespan

Even though pines are often fast-growing they are seldom grown on very short rotations. Contributing factors are,

- Not having the extreme relative growth rates that allow mean annual increments to culminate at very early ages
- Their wood being more valuable for solid-wood products than for pulping or board products, also militating against extremely short rotations
- Wood quality tending to be low, especially for the more lucrative current uses, in very young trees.

The relatively long lifespan can accentuate risks related to any tree-improvement technologies in several ways. A crop can be exposed to risk over a longer period. A delayed failure, which may still occur before profitable salvage is possible, will carry the compounded costs of crop establishment, tending, and protection. Furthermore, a delayed failure may involve plantings made over a number of years, which can be especially damaging in itself and preclude any rapid recovery of the forest-growing enterprise.

Natural Silvics

Pines are typically strongly light-demanding, like many species that are either pioneers in an ecological succession or else are involved in fire-induced climaxes. As such, they are usually far more conveniently grown in pure, even-aged stands (Burdon, in press). Thus growing pines for convenience and high economic returns entails the risks that are inherent in growing pure, even-aged stands, although the major part that pure, even-aged stands often play in the natural ecology is likely to reduce the inherent riskiness of the system.

Soil and Climatic Tolerances

Pines are generally adapted to relatively low soil fertility (Burdon in press), which has various implications. Large areas of land can thus be available for growing pines, which affects the potential scale of risk. The low fertility demands are likely to be related to the limitations in early growth potential, which affect crop lifespan. Moreover, the land that will be available for pine plantations will often represent sites where intensive intervention to counter some risk factors (e.g.. certain diseases) may not be economically feasible. The climatic tolerances of many pines will also favor their use on sites imposing such constraints.

Wind Pollination

The wind pollination has twofold significance, in its potential for the long-distance spread of genetic material into exotic and native stands (e.g., Sedgley and Griffin 1989: DiFazio et al. 1999), and its likely impact on the level of diversion of resources into reproduction. While most of the pollen settles within short distances from points of release, dense pollen clouds can still occur at considerable distances from large areas of the stand (Lindgren et al. 1995). However, if the species are exotics, the ecological and political concerns over pollen contamination are reduced, compared with species that are native to the growing region, especially if none of the native species are interfertile with the plantation species. In fact, there are relatively few situations where such interfertility is likely to arise with pines.

The diversion of resources into reproduction can be major (e.g., Fielding 1960; Cremer 1992), and is all the more significant because the pollen component represents ‘high-grade’ biomass in having a high content of nutrients. Suppression of reproduction is an attractive goal, offering up to 100% reduction in pollen flow and redirection of energy flows potentially resulting in increased timber production (Ledig and Linzer 1978). Genetic engineering strategies exist to achieve this goal to a high degree, including the expression of cytotoxic genes in reproductive tissue, influencing reproductive pathways through homeotic genes, and the suppression of specific genes involved in reproductive development (Strauss et al. 1995). None of these technologies however can guarantee a complete barrier to reproduction when used on their own, and a pyramiding strategy may be more successful in completely controlling reproduction in a given stand. This is of particular importance in areas where interfertility with native species can be expected.

Other, more subtle considerations can arise. For instance, elimination of pollen cone formation in pines may change crown configuration by eliminating zones of shoot without foliage. Thus, the genotypes with the best crown configuration for crop productivity before suppression of pollen cone formation may not be so after this has been achieved. Hence there can be complex interactions between genetic engineering and classical breeding, which could lead the unwary into unexpected losses. Complex interactions may arise among traits being addressed by conventional breeding, and some argue that they may be far less important because of the less radical changes that it will bring within a short time frame. This conclusion however, still lacks supporting data and more research is required to fully understand this issue.

Another environmental aspect related to sterility considerations is the importance of pollen-feeding native insects and birds. It may be appropriate to design strategies that still allow inviable pollen production and the normal food chain in a given ecosystem to remain intact.

Outbreeding Behavior

Pines, with very few exceptions, are natural outbreeders (Richardson 1998; Burdon, in press), which has some important implications. The tree-to-tree genetic variation can be important for population resistance to diseases (Thielges 1982), which may not always fit conveniently with the clonal systems that may be needed in order to use genetic transformation. The tree-to-tree genetic variation that is typically associated with the outbreeding behavior is likely to make genetic gains readily available from recurrent selection within existing populations. At the same time, such genetic improvement can be a crucial platform for optimizing on the improvements achievable through genetic modification, because the merit of a transformant will inevitably be limited by the general merit of the recipient genotype.

Exotic Status

Where the pine species is grown as an exotic, genetic contamination of its natural stands is not usually an issue, although hybridization with some other pine species might very occasionally be. If *ex-situ* gene resources are to be maintained, as potential sources of new germplasm that is unrelated to existing material in breeding populations, any pollen contamination from commercial stands is generally very unwelcome. (Burdon and Kumar, in ms) If it comes from transgenic material it is likely to be even more so, if only because it could raise a whole new area of public concerns. However, suppression of pollen production would be sought in the interests of improving net production as well as allaying concerns over containment.

COMPARISONS OF EUCALYPTS WITH PINES

Call for Genetic Transformation

Eucalypts can be highly vulnerable to weed competition and very subject to defoliation by insects (Cromer and Eldridge 2000). In that resistance to herbicides and insect attack are both being widely pursued through genetic modification, we have two areas where the use of transgenics will tend to be particularly attractive for eucalypts. Interest in the respective areas is exemplified by Edwards et al. (1995) and Harcourt et al. (1995).

Factors Mitigating Risks of Using Transgenics

The insect pollination of eucalypts, as opposed to wind pollination of pines, will tend to reduce the risks of long-distance gene flow, meaning that containment is inherently easier, creating less call for suppression of reproduction. Eucalypt plantations have, until quite recently, been almost entirely exotic, unlike huge areas of intensively cultivated pine plantations (e.g., *Pinus taeda* and *P. elliottii*) within their native ranges. This has made potential gene flow into natural populations far less of an issue, but a recent upsurge of establishment of eucalypt plantations in Australia is changing the picture (Cromer and Eldridge 2000). The very short rotations on which eucalypts are often grown, usually for pulpwood or fuelwood, should in some ways mitigate the impact of crop failure. Moreover, the flat or easy terrain on which eucalypts are very often grown, and the associated site cultivation, should help facilitate protective intervention against, say, a disease that may flare up, whether or not it arises specifically in transgenics.

Factors Accentuating Risks of Using Transgenic Eucalypts

Interfertility among eucalypt species is common, which favors cross-pollination among species. This may be accentuated by the way in which flowering seasons can be greatly altered by exotic environments, thereby creating overlaps between species in flowering times, which can break down natural reproductive isolation. However, any impact of interspecific pollination is likely to be confined to *ex-situ* genetic resources growing very close to transgenic crops. The short rotations that may appear superficially to be a mitigating factor, may not work entirely this way; where eucalypt plantations feed highly capitalized pulp mills the costs of supply disruption through crop failure could be very high, unless alternative pulpwood supplies are readily available. This is, however, a management problem that is associated with any use of biological systems for production processes and risks are associated with conventionally produced material and transgenic material alike. Moreover, in such cases the plantings made in just a single year, which might all be exposed to some unsuspected risk factor, would represent a considerable fraction of a plantation estate.

RISK CATEGORIES

The risks may be classified in various ways. The first breakdown that we are adopting is into

- *Development-related risks,* involved in pursuing and developing genetic modification (GM) or genetic engineering
- *Deployment-related risks,* associated with the operational use of genetically modified crops.

A pervasive problem in evaluating risk is that many of the risks mentioned in relation to genetic engineering are perceived and to a great extent unsubstantiated, and that at least a considerable proportion of them will not be real. Much has been written speculatively about potentially devastating effects related to GM. However we wish to point out that some of the risks associated to the products of genetic engineering are largely shared with the products of conventional breeding or even of natural evolution.

Development-related Risks

As with any new or very immature technology genetic transformation will have its technological risks (Burdon 1992), relating to whether it will actually succeed, or at least do so without prohibitive development costs. A spread of risks, in respect of the genetic modifications that are pursued, may be indicated. While this may entail considerable dispersal of effort, risk management is an expected component of applying any technology (Anon 1999). Consequently, risk related to other forest plantation technologies should be reconsidered and analyzed in context and in comparison with new technologies. This area has indeed been neglected considerably over the last decades, and despite the fact that both clonal propagation and conventional breeding have generated examples of non-desirable effects (consider for instance somaclonal variation).

A related area of risk, which is at the fringes of our brief but can have major economic implications, is possible misallocation of resources between GM and conventional breeding (Burdon 1992; 1994; 1998).

Deployment-related Risks

Briefly, these risks may be grouped into some partly overlapping categories:

- Ecological
- Human health
- Cultural objections
- Crop vulnerability.

Ecological risks

Ecological risks involve, in principle, two avenues of gene flow:

- Pollen flow into natural populations, invasion of natural ecosystems through seed produced by transgenic crops, and transgenic cultivars developing a weed potential in their own right
- Spontaneous HGT in the field (Syvanen et al. 1994; Dale 1999; Mullin and Bertrand 1998).

All such risks will depend strongly on the introduced gene(s) conferring a material fitness advantage in the wild. Often there is no reason to expect any such advantage, and any effect will always have to be evaluated in context with the particular environment the organism is placed in. Also, any effect and its magnitude will have to be compared with those arising from the use of already accepted and practiced tree-improvement technologies. Further, the issue of HGT is far from trivial in that if it occurs at reasonable frequency, its impact may not be any greater than the simultaneously occurring horizontal gene transfer of identical genes in a natural environment. Horizontal gene transfer may very well exist—and that would be an indication that the "total genome" of all organisms taken together is indeed more flexible than previously expected (Jain et al. 1999).

Among the perceived risk categories for transgenic forest plantations, HGT is perhaps the most difficult to discuss on a rational, properly informed basis. Also it poses the problem of not being amenable to risk spread and being potentially irreversible if it occurs. It is a frequent phenomenon in nature, particularly between bacterial species (Lorenz and Wackernagel 1994; Eisen 2000), but HGT into and between higher organisms has also been postulated and occasionally demonstrated (Nielsen et al. 1998; Kado 1998). The transfer of specific DNA sequences from *Agrobacterium* to cells of plant species during an infection process, can also be regarded as HGT. It is currently the only known example of a type of HGT that not only occurs frequently in nature, but also involves the transfer of DNA from a microorganism to a higher organism. The transfer of DNA from gut bacteria to cells lining the mammalian gut has occasionally been postulated, but solid scientific data to support this hypothesis has not been produced. The unraveling and study of HGT has so far has led to the notion that the total genome, including all organisms, may in fact be highly flexible (Jain et al. 1999; Lawrence 1999), and that horizontal gene transfer is a common tool of evolution (de la Cruz and Davies 2000; Woese 2000). It is therefore highly questionable whether GM would add materially to the effects of natural mutation combined with any natural capacity for HGT, given that mutation surely occurs frequently among the vast numbers of individual microorganisms.

Looking at the situation slightly differently, the probability of harm arising from HGT represents the probability that HGT will occur, multiplied by the probability that, if it has occurred, harm will result. If the probability of occurrence is high, that will almost certainly be part of a situation whereby HGT occurs regularly but, even in conjunction with ubiquitous mutation in microorganisms, seldom if ever does any ecological harm. Thus if there a high probability of HGT occurring, it seems very unlikely to be ecologically harmful if it does occur.

Human health risks

This category is technically problematic, in the sense of generally representing tenuous possibilities, even with most food crops, but vehement perceptions are now a fact of life (Ho 1998; Antoniou 1996). The only foodstuffs provided directly by pines are seeds, and the species concerned are not major plantation crops. Indirect food production occurs through collection of fruiting bodies of edible symbiont fungi, which again raises the issue of HGT (Droege et al. 1998). Other, very hypothetical possibilities arise through the role that pine material might play in natural food chains, or in incidental contamination processes (e.g., through deposition of pollen on food crops). Consider however, that a gene transformed into pine can contaminate food resources, but it can also flow from its original host organism to potential foods. The difference between the two sources appears significant to opponents of genetic engineering, but the data to substantiate their claims are not forthcoming.

With issues of human health and ecological side effects many parts of society call for applying the precautionary principle. On the other hand, many of the undesirable possibilities invoked seem remote indeed and scientific data to substantiate claims are still not produced. Concerning foods and food chains, even secondary products of the very small number of new genes that would be used would arise in the context of many thousands of natural products that are routinely detoxified in the small amounts that occur (unless food spoilage is involved, such as the production of large amounts of aflatoxin).

Cultural issues

It has become evident that significant parts of society regard the transfer of genes from one organism to another as against their religious or cultural beliefs. Such beliefs, whatever their origins, are often extremely difficult to address and overcome, because they can automatically seal people off from the processes of education and open-minded discussion of facts and foreseeable consequences of using transgenics. Further, it is suspected that if such religious and cultural concerns were applied even-handedly, there would be objections to many other modern-day human activities that currently pass almost without thought. On a narrower front, genetic engineering also must be reviewed critically in comparison with older technologies, such as breeding and the mass clonal propagation used to deliver genetic gains.

Crop vulnerability

While this issue has been little publicized, we see it as being potentially important, and will give it special attention. The economic significance, and thence the social significance, are potentially enormous.

Categories of technical risk, primarily associated with deployment of transgenics, are summarized in Table 1, along with risk properties, predisposing risk factors, and appropriate types of countermeasures. Putative risk factors relating to possible cultivar decline associated with genetic transformation are summarized in Table 2. These two Tables provide a backdrop for much of the ensuing discussion.

Crop vulnerability can possibly arise from genetic modification in various ways (Table 2), some direct and some indirect. The more direct ways

Table 1. Summary of categories of technical risk, putative risk properties and risk factors, and potential approaches to counter the risks.

Risk category					Type(s) of prime
General	Specific	Likelihood	Potential severity	Predisposing factor(s)	countermeasures
Related to technology development	Transient gene expression	High	Troublesome, but in some situations could	Transformation technique, gene(s) concerned?	Careful testing
		even be advantageous			
Ecological	Direct contamination of ecosystems	Largely precluded by exotic status of genera in question	Problem in managing *ex-situ* gene resources	Wind pollination, [species native to area, presence of interfertile relatives], efficient seed dispersal	Conferring sterility
	Horizontal transfer	Frequent amongst microorganisms, unlikely for higher organisms	Most unlikely to be significant	Highly dependent of selective advantage of transgene(s) in field	HGT mechanism needs to be better understood. Need for more research.
Human health	Allergenicity	Extremely low for transgenes	Most unlikely to be serious	Wind pollination, quest for durable heartwood	No specific measures
	Food contamination	Extremely low	Most unlikely to be serious	Conceivably applicable to nectar (eucalypts) or edible fungi (pines)	No specific measures envisaged
Crop vulnerability	Cultivar decline/failure	General hazard, widely variable	Very high at top of range (see Table 2)	Various (see Table 2)	Various (see Table 2)
	Non-durability of resistance	Potentially significant	Potentially troublesome.	Relying on single genes of large effect for resistance.	Using multiple resistance factors (with its own risks)

Note: Risk categories need not be mutually exclusive. For example, horizontal transfer could theoretically lead to food contamination, while non-durability of resistance could cause cultivar decline/failure.

Table 2. Summary of factors believed to generate risks of cultivar decline/failure, with suggested ranking (in descending order) of risk potential for different categories within each factor, and preferred countermeasure(s) for each factor. Note that many of the conclusions here must be based on opinion, for lack of solid data.

Factor	Ranking of categories within factor	Remarks
Transgene source	Synthetic genes > genes from distant taxa > genes from close relatives > genes from within species*	Risk spread a potential defense apart from choice of source
Transformation method	Biolistics > *Agrobacterium*	*Agrobacterium* poses greater technical difficulty with taxa concerned. Risk spread potentially very effective defense.
Role of transgenes	Structural genes > regulators *or* anti-sense sequences	Lower rankings unclear
Type of genes	Homeotic genes (e.g flowering) > other genes	May constitute a key hurdle in suppressing reproduction
Magnitude of gene effect	Large > small	Major genes preferred nonetheless, for various reasons
Number of gene insertions	Multiple > few > single	Multiple insertions may be needed on regulatory grounds, or to confer durability of resistance
In-vitro culture technique(*i*)	Single-cell lines > organogenetic cultures (*ii*) Adventitious shoots > axillary shoots	

* Condition favoring use of traditional breeding.

involve side-effects of the action of new structural genes or of modification (either over-expression or down-regulation) of the action of existing genes; side- effects of the process of inserting the new DNA sequences; or silencing of newly introduced genes (Finnegan and McElroy 1994; Matzke and Matzke 1995). Similar effects can be expected from the combination of sets of new genes that have the potential to influence each other, creating undesirable effects. Indirect effects can arise, for instance, from the impacts on deployment practices resulting from the use of transgenic material, such as generating a shift towards use of clonal material, or from extending the environmental range of a species after inserting a disease resistance gene only for the resistance to break down through pathogen mutation (Burdon 1999).

What may be the classic object lesson is the case of the corn blight epidemic in the United States in 1970 (Levings 1989). It resulted from a combination of massive reliance on the Texas cytoplasmic male-sterility factor in order to produce the hybrid maize, an unsuspected side-effect whereby that factor created extreme susceptibility to a new strain of the pathogen, and the eventual appearance of that pathogen strain. Admittedly that involved a mutant gene in an organelle genome and it did not involve genetic modification, so it is not strictly parallel to what would be achieved by genetic transformation involving the nuclear genome. It is a matter of opinion as to how relevant this case is to genetic transformation in general. Also in the realm of opinion is whether, even if it is relevant, it is so to a broad spectrum of genetic transformations or specifically to ones involving flowering. One breeding scientist's view is that it prudent to assume the former, even though the homeotic nature of various flowering genes gives reason to believe that risks might be higher when suppression of flowering is involved. However, this case can also be seen, at least by one transformation scientist, as an illustration of how unwanted and unexpected (and sometimes hazardous) effects are not restricted to the use of material produced by GM. Classical breeding efforts can lead to exactly that as well, although the case in point, while arising in the era of classical breeding, was achieving something that is now being pursued by GM. Any transgenes that get used, and their 'downstream' products, will admittedly be much better characterized than this male-sterility factor, but that will not eliminate all possibility of nasty surprises.

The precautionary principle

All told, this is an area of considerable uncertainty, where there is scope for enormous variation in subjective assessments of the hazards, particularly those relating to ecological side effects and human health. At one extreme there will be those who see virtually limitless need to apply the precautionary principle. Among them there will be those who may see individual hazards as being slight, but the different hazards as being so numerous as to generate a significant total hazard; they will tend to be exasperated by what they see as the uncritical enthusiasm of the optimists. At the other extreme, there will be those who see the hazards as being very minor, and they may include devotees of Lovelock's Gaia principle, whereby a biota, and its interdependent environment, have an enormous inherent resilience. For many of the optimists the precautionary principle might be seen, with much irritation, as something like allegations of child abuse in an acrimonious custody battle, easily made but once made are inherently very hard to disprove. It is also interesting to note that there is no commonly agreed ' precautionary principle', as more than 35 different versions exist.

A major issue related to genetic engineering of all crops is the lengths to which some parts of society try to impose viewpoints that, while they may dearly held, seem most improbably alarmist in the context of all available evidence. It is observable that many claims made are based on lack of scientific understanding or even a refusal to accept a scientific approach to the issue. Very often doomsday scenarios are presented, with little or no scientific evidence to back up those statements. This has become particularly obvious in submissions to the Royal Commission on Genetic Engineering in New Zealand (RC), where proponents and opponents of genetic engineering were asked to present their cases (www.gmcommission.govt.nz). A witness brief by Dr. Elaine Ingham of Oregon State University affiliations, who testified for the Green Party of New Zealand, cited to the RC a nonexistent paper in support of a claim that genetically modified *Klebsiella planticola* bacteria had, if released, the potential to devastate plant life on the planet. When the non-existence of the paper was exposed, Dr. Ingham and the Green Party of New Zealand had to apologize to the RC for misleading them (Walter et al. 2001; Fletcher 2001). Furthermore, the use of data by Dr. Ingham to support her case in front of the RC has proved to be scientifically unsustainable. Her conclusions in relation to the potential harmful nature of the bacterium were made on the basis of a single experiment in the laboratory where controls were not properly applied. Also very important is that a naturally existing variant of *Klebsiella planticola* shares the key, alcohol-producing characteristic of the genetically engineered bacterium (Jarvis et al 1997), without showing any harmful effect on plant life in its environment.

Low-risk Applications

Uses of genetic transformation will not be confined to operational use in commercial crops. It has great promise as a research tool. Transgenes can be used to study pathways of gene action and their effects on phenotype, as an aid to identifying appropriate breeding goals, and/or helping identify desirable genes that might be exploited by enhancements of classical breeding. With purely research-oriented applications some may still see risks, notably in the area of containment, but the magnitude of such risks should be only a small fraction of that of the potential risks associated with operational use and deployment.

GENETIC MODIFICATION COMPARED WITH EVOLUTION AND CLASSICAL BREEDING

New genes have appeared and spread through populations throughout evolutionary history, even though certain genes that perform basic functions may be highly conserved. It is evident that various processes that allow the transfer of DNA sequences from one organism to another, such as HGT between bacteria, *Agrobacterium* gene transfer to plant cells, and virus infections, have all contributed to variation and long-term evolution (see above). It is instructive, though, to compare the process of introducing a transgene with these natural processes whereby a gene can spread through a population. In nature, a new allele will typically appear as a rare variant. It can have various fates, which range from rapid, often random extinction, through persistence at low, if variable frequencies, to spreading through the population more or less slowly and ultimately becoming fixed. The exact fate will depend whether it is selectively neutral or nearly so, on the one hand, or significantly advantageous, on the other, plus large elements of chance. Alternatively, new alleles can enter the population by migration (usually pollen and/or seed dispersal). Either way, a new allele will tend to enter the population on a 'toe-in-the-water' basis. If such a gene proves deleterious, even with some time lag, it will be eliminated or remain at a low frequency with minimal cost in population fitness. Population bottlenecks, of one sort or another, can accelerate the process and even set evolution on new courses, but will be accompanied by risks of extinction. Yet even a population bottleneck would seldom, by itself, bring a gene to a frequency that would immediately allow it to pervade the population. Viruses have the potential to spread genes rapidly through populations of many organisms and even across species barriers. However, viruses for pines or eucalypts have not yet been described.

Use of a transgene, by contrast, can immediately raise the effective frequency of a new gene to 100% in a portion of the crop's range, if its action is fully dominant, which would create 100% exposure to any adverse side effects. Clearly, though, there are various categories of transgenes, ranging from constructs that modify the expression of existing structural genes, which are likely to present relatively low risks, to structural genes of totally novel function within the species, for which the attendant risks may be much higher. Although HGT may lead to rapid spread of genes through populations of some organisms, it appears most improbable that it could have any serious impact on a commercial plantation or its associated biota.

Artificial selection is in several respects intermediate between genetic modification and natural evolution. In that it depends strictly on genes that have occurred naturally within living populations of a given organism, it stands close to evolution. However, the intensive and highly directional selection that it can entail can generate closer parallels with use of transgenics, especially if technology can be used to select for specific genes that have major phenotypic effects.

Operational use of transgenics can thus lead to more rapid and complete exposure to risks of adverse side-effects of specific genes than can be expected in natural evolution or even classical artificial breeding, in which massive substitutions of particular alleles will tend to be far slower (except for high-risk cases of some complete clonal monocultures). This does not mean that undue risk exposure cannot be incurred with conventional breeding, particularly when combined with mass vegetative propagation for clonal forestry (e.g., Libby 1982; Burdon 2001), but it does mean an essentially new area of risk which poses its own management challenges.

RISK PROFILES AND RISK MANAGEMENT

Our focus here is on deployment-related risks (Table 1). For any risk there will be a profile of probability in relation to severity. In principle, this will conform to a mathematical function, but one that is seldom closely defined; typically there will be a high probability of minor losses trailing away to much lower probabilities of much higher percentage losses. The distinction between seriousness and severity can be illustrated by how a total loss, if it involves only a small, isolated plantation, may not be serious, provided the owner has a good risk spread. In fact we are typically looking at low probabilities of 'disaster' outcomes, albeit with almost no idea of exactly how low they are, although some transformations will be seen as less risky than others (Table 2). On the other hand, the length of rotation can make such disasters very serious, depending on the exposure to specific risks. The potential seriousness, even if the probability is low, demands some form of risk management (Burdon 1999; 2001). If active countermeasures against risks cannot be well targeted, yet risk spread is feasible, then risk spread is strongly indicated.

In practice, we will be working with very little quantitative information or, in the jargon, with great uncertainty. True, there are many cases where transformation has been associated, directly or indirectly, with disastrous effects on fitness, but they will often be manifested in cell lines that are obviously not worth committing to field trials although the exact reasons for their state are seldom identified. For the material that has sufficient promise to be tested in the field, the risks, in terms of the probability function in relation to severity, remain very uncertain. However, the potential seriousness, which may be extreme in the case of delayed manifestation of induced disease susceptibility, may dominate the appropriate risk management. A significant period of field testing (which can be preceded by laboratory testing and physiological studies) seems essential in some, but not all cases, to eliminate effects such as greatly enhanced susceptibility to climatic damage (say, in the case of a transformant for wood chemistry that might adversely affect the mechanical stability of the tree). However, such testing will only reduce the risks, rather than totally eliminate them, and in the short term, is liable to greatly erode the potential time savings in using GM compared with conventional breeding. The transformation scientist, however, looks to the future when, with the risks of transgenes being much better known, the field testing can be foreshortened to the point of allowing major time savings using GM compared with conventional breeding.

In general, society has to make decisions on the use of this new technology. This will involve weighing up the prospective benefits against the risks. In weighing up the risks there will be considerations of how the risks can be addressed by risk spread and/or active countermeasures against the risk (Table 1; see also Burdon 2001), and what remaining level of risk may have to be accepted if the technology is to be used. This is true however for any technology in use, and people are always prepared to accept some risk, as long as sufficient benefits are realized or anticipated. The amount and level of field testing of transgenic material before commercial release has to be guided by scientific argument, but also by the level of residual risk a society is prepared to take.

In the present context of possible use of transgenic plantations, risk spread is seen as a crucial component of risk management. It appears especially appropriate for addressing potentially very serious events of low, but very uncertain probabilities. An ideal risk-spread strategy for GM or conventional products should be based on the following planks (cf Burdon 1999):

1. As a starting point, using a diversity of recipient genotypes,
2. It should involve different, and as precise as possible, gene-insertion events,
3. Use of a number of different transgenes or regulator constructs in order to achieve a particular objective,
4. It should attempt to avoid the co-transfer of unwanted DNA sequences.

Requirement 3, however, may be difficult to meet with genetic modification designed to eliminate all reproductive activity, which would be desired for reliable genetic containment as well as optimizing resource allocation for crop production. However, opinions may vary on the need for complete suppression and, for meeting less stringent requirements of suppression, a number of independent suppressor genes that could be available in various combinations.

Meeting this requirement may, ironically, be impeded by regulatory mechanisms that require separate processing of all elements of risk spread, proliferating costs of compliance, rather than addressing an appropriate spread of risks as a single ‘package’.

For very low-probability events such risk spread, where it is applicable, can reduce the probability of catastrophic crop failure by orders of magnitude. To express this in another way, the probability of simultaneous ‘disasters’, each of low probability, involving an unacceptable proportion of a set independent transformations is should become almost vanishingly low. On the other hand, such use of multiple transgenes will increase the theoretical risks of HGT, but by no more than a factor of the number of risk-spread elements—if no such element can be identified as incurring elevated HGT-related risks. Thus, the relative increase in HGT-related risks should be far less than the relative reduction in risks of GM-related crop failure.

For the longer term, leading into active countermeasures against the risks, more research into gene integration and expression characteristics, and research on the influence of transgenes on natural ecosystems, should help to define constructs that carry a significantly lower risk potential. Examples are new strategies for the selection of transgenes avoiding antibiotic selection or the complete elimination of selective markers (Joersbo and Okkels 1996; Haldrup et al. 1998; Sugita et al.

1999). Although a perceived negative effect of antibiotic-resistance markers is not substantiated by scientific data, and it is possible to involve antibiotics that are of no further clinical interest, the avoidance of such markers may increase acceptance of genetic engineering by the general public.

There may be a call to use multiple transgenes simultaneously in cultivar genotypes, based on technical needs and/or regulatory requirements for genetic containment in field deployment. This has a potential, which is admittedly very speculative, to increase greatly the inherent risks associated with deployment of transgenic material (Burdon 1999). Not only will there be a straightforward accumulation of the risks associated with each individual transgene, but increasing numbers of transgenes will exist in greatly increasing numbers of combinations that might generate adverse interactions between different transgenes—if such transgenes involve significant risk factors (Table 2).

CONCLUDING COMMENTS

The focus has been largely on the risks associated with genetic transformation. However, they need always to be balanced against the prospective benefits, noting that the benefits will require critical examination in respect of both their validity and their dependence on the use of genetic transformation. The risks must also be placed in perspective with those of alternative methods of achieving the same goals, e.g., conventional breeding, which will have its own risks, although these are much more readily accepted by society at this point in time. Nor should it be forgotten that GM can be used as a research tool, largely without incurring the risks attendant upon operational use in commercial crops.

A breeding scientist may argue that the risks associated with conventional breeding may be more easily managed than those of transgenics, which typically involve new genes of large effect. However, a transformation scientist may consider the less predictable risks of conventional breeding that are associated with many unidentified genes as greater than GM of one characterized gene. Thus the comparative risk potential for the alternative technologies remain arguable. Possibly much more important is that GM can in some cases lead to more rapid and complete exposure to certain risks. For some conventional breeding products, however, this problem can also arise.

Experience with other technologies, notably biotechnology, is that nature often springs nasty surprises, just when one imagines that problems are solved. Resistance to antibiotics, the dangers associated with blood transfusions, and the corn blight epidemic of 1970 are just three of the most obvious examples. They illustrate, however, the need for a comprehensive risk/benefit analysis and an informed decision on what level of risk we are prepared to accept for obtaining a certain level of benefit, in a context of an unavoidable element of uncertainty. Notwithstanding the problems of antibiotic resistance, no one would seriously demand that we stop using a key weapon for combating some of the most serious diseases from this planet. The benefits of genetic engineering are becoming obvious in many areas. In medicine they are huge, and in many areas they are very widely accepted. In agriculture they are also great, but are now beset by problems of public acceptance. The example of Golden Rice, a genetically modified and vitamin A enhanced rice that has the potential to save hundreds of thousands from blindness, is just one example. In forestry the prospective benefits are also great (Strauss et al. 1999), but the ecological ramifications pose problems of acceptance while the time frames for plantation crops both create attractions for use of GM and accentuate certain risks. The lesson is surely that those who manage the applications of technologies like genetic modification need to have good advance preparations for surprises and they need to have management tools to minimize any impact on the environment, human health, or economic prosperity.

We can make our own technical judgements of risks, and enhance them with quantitative risk analysis, and devise risk-management strategies. Yet we cannot ignore public perceptions, however exasperated we may become at times. Moreover, even the occasional scientific fiasco can have strong and enduring effects on public confidence. Subjective judgements on the part of the public may be perceived vividly by scientists, but scientists can never avoid areas where they must be guided in some degree by their own subjective judgements.

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Use of Transgenic Resistance in Plantation Trees: Efficacy, Risk, and Integration with Other Pest Management Tactics

Kenneth F. Raffa

ABSTRACT

Transgenic expression provides some opportunities for pest resistance in trees that cannot be achieved by other means. However, environmental risk assessment poses some special difficulties with trees. These relate to the long time scale of host relative to pest generation times, the large spatial scale of some plantation systems, and the multiple uses and ecological functions of adjoining conspecific plantation and native trees. Several issues are addressed: 1) How does the scale at which we evaluate GMO's affect our estimate benefits and risks? 2) What risks can be identified, and how can they best be addressed? 3) What experiences provide the most sound precedents upon which to evaluate transgenic trees: Should we evaluate them as pesticides deployed by another means, traditionally bred resistant varieties, or planned introductions of biocontrol agents? The integration of multiple pest management tactics, implementation of biotype management strategies, examples where general principles can be more valuable than specific details, and weaknesses in current funding approaches to risk assessment are discussed.

Nearly 20 years have passed since the first report of transgenic expression in plants (Meeusen and Warren 1989). It's been over 10 years since the development of transgenic Bt resistance in hybrid poplar against tent caterpillars and gypsy moths (McCown et al. 1991; Robison and Raffa 1994). Yet we still have only a limited ability to assess the long-term implications of genetically modified organisms on forest ecosystems.

I'd like to suggest four reasons for keeping the issue of environmental safety of genetically engineered trees at the forefront: First, trees pose some inherently distinct problems. Unlike agricultural crops they have generation times much longer than those of their major pests. Also, trees are both commercial plantings and components of native ecosystems. The same species grow adjacent to each other, and provide multiple ecological functions and human resources. Second, the track record of agricultural transgenic plants is too brief a time scale to allow full evaluation (Parker and Karieva 1996; van Embden 1999). By comparison, problems arising from injudiciously selected biological control agents, calendar application of pesticides, vertebrate predator elimination, and fire suppression often were not detectable until many decades after implementation. In general, the longer the time lag between implementation and the appearance of a problem, the greater the difficulty in addressing it. Third, pest managers and seed producers of agricultural crops have implemented specific practices aimed at preventing biotype evolution (Roush 1997), but parallel practices have not yet been developed for trees. This reflects both the greater emphasis placed on agriculture and the difficulties of working with trees. Fourth, government-sponsored research on Risk

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Assessment of GMOs has fostered a false sense of assurance. As anyone who vies for competitive grants can attest, a key to success is defining tight, narrowly focused experiments that can be conducted under controlled conditions over short time frames, using organisms that lend themselves to simple bioassays. Unfortunately, the key questions about environmental safety are long-term, complex, and operative across multiple trophic levels.

My discussion will focus on transgenic resistance against insects in plantation trees. However, I hope that some of the general principles I discuss can be applied to other types of transgenic properties. I also need to emphasize that this discussion cannot be extrapolated to self-regenerating trees, dissemination by insect vectors, etc.

POTENTIAL AND RISKS OF GENETIC ENGINEERING

The advantages provided by genetically engineered pest resistance are significant. Insects and pathogens are major limitations to tree productivity (Can. FS 1994). Moreover, the conditions under which trees are grown commercially, usually even-aged, evenly spaced monocultures, make them more manageable for the producer, but also much more susceptible to the insects that consume them. Breeding for resistance is far more difficult in trees than inannual crops, for obvious reasons of size and time. Moreover, trees are faced with complexes of insects, and it is difficult to select for resistance against all of them. It is especially difficult when one insect prefers the very group of phytochemicals that confers resistance against others (Raffa et al. 1997).

Deploying pest-resistant trees may allow for reduced input of insecticides. This has already been demonstrated in some agricultural crops. Moreover, enhancing productivity on intensively managed lands may alleviate demands on the land base, thus allowing more regions to be set aside for wilderness and biodiversity objectives. Transgenic capabilities may also help us respond more quickly to invasive species, which are an increasing threat associated with heightened global commerce.

A number of potential risks have also been identified. These include evolution of insect biotypes resistant to the transgene, adverse direct and indirect effects on nontarget organisms, and alteration of ecosystem processes such as nutrient cycling and pollination. Molecular biologists and ecologists agree on both the potential benefits and risks of transgenic plants, but differ on the degree to which they emphasize each. I think this reflects differences in the level of biological organization at which they work. Ecology is the study of interactions. Ecologists deal with systems that are open, complex, and to some extent undefined. Molecular biologists deal with systems that are closed, controlled, and simplified to the best of their ability. There is an inherent tension between the reality of the field vs. the precision of the laboratory. When a molecular biologist encounters a difficult problem, resolution often comes through either a technical advance or an improved insight into a specific mechanism. That insight is often achieved by removing extraneous noise from the system. In the case of ecologists, our ability to resolve a question is usually improved once we identify additional factors that are impacting on our unit of study. Our previous lack of understanding is overcome when we recognize how to introduce complex feedback into what we previously thought was a simpler system.

Let me provide some illustrations. Sheep production is an important industry throughout much of western North America. Coyotes can pose significant problems, by feeding on lambs. So range managers set out to eradicate coyotes. Early attempts were unsuccessful: the coyotes were too clever and avoided the traps. Eventually trap and bait technologies improved, and coyote populations decreased. Thereafter sheep populations crashed too. The reason was that range biologists underestimated the complexity of the system. Coyotes also eat rabbits, which soared after coyotes were eliminated, devoured the grass, and starved the sheep. Similar experiences occurred with attempts to remove wolves to favor beaver fur production, with fire suppression, and with DDT applications against spruce budworm. The general lesson is that when you transfer technology from closed, controlled conditions to open complex systems, there are almost always unforeseen parameters that affect system behavior.

Based on their different experiences, molecular biologists and ecologists tend to ask the question differently. Molecular biologists frequently ask, "What are the specific risks that can be anticipated based on the properties of a specific product?" This reflects a belief that assuming a risk might exist without the ability to characterize or quantify it is unscientific. In contrast, ecologists ask: "What is the evidence that specific information derived from closed systems over short time intervals can be extrapolated to multiple interactions in open systems over longtime periods?" This reflects a belief that assuming extrapolation in the absence of proof is as unscientific as performing experiments without testing whether Heisenberg's Uncertainty Principle is satisfied. To ecologists, deployment of GMOs is a classic scaling problem, and there are not many examples where extrapolating across scales yields consistently predictable relationships.

Resolving such dichotomies between the experiences and assumptions of molecular biologists and ecologists is one of the most important steps in both maximizing the benefits and minimizing the risks of genetic engineering. Ecological understanding can be useful both in identifying risks inherent in extrapolating from closed to open systems, and in integrating multiple sources of insect mortality to improve efficacy. Likewise, molecular methods will provide some of the most valuable tools for ameliorating risks identified by ecologists (Raffa 1989).

DEFINING RISK ASSESSMENT

How can we integrate molecular and ecological approaches? I suggest starting with a point of common agreement. This is provided by the first National Academy of Sciences (1987) report that has shown a remarkable ability to stand the test of time. This report emphasized that the "product not the process" should be the focus. This report stated, "Assessment of risk should be based on the organism, not the method of engineering." Remarkably, a white paper by the Ecological Society of America independently reached an identical conclusion (Tiedje et al. 1989): "transgenic organisms should be evaluated and regulated according to their biological properties, rather than according to the genetic techniques used to produce them."

The *product not process* guideline is sometimes misinterpreted to mean that environmental concerns with GMOs are unwarranted. Nothing could be further from the truth. This principle dismisses scientifically unfounded concerns that a particular product may exert an effect simply because it was genetically engineered. But it also focuses attention on interactions: How will this organism interact with other organisms in complex, open ecosystems, over long periods of time? Moreover, the *product not process* perspective yields a corollary: "If the product not the process is critical, then expertise in the methods of genetic engineering is not directly relevant to predicting how novel organisms will interact with ecosystems" (Raffa et al. 1997).

There is no uniform agreement on how to approach risk. One approach is to list every conceivable adverse consequence. Perhaps this isn't a bad starting point, but it loses scientific validity if does not proceed to a critical evaluation of each potential harm, or if it extrapolates uncritically from artificial conditions to ecosystem levels. I see three disadvantages to this approach. First, it can lead to lost opportunities. No undertaking is without risk, and refusal to manage it can preclude realization of the benefits described above. Second, well-intended environmental policies, like well-intended technologies, can have unintended consequences. An example is the Delaney Clause, which was intended to prevent registration of carcinogenic pesticides, and in the process favored more toxic compounds. A third disadvantage is that it distracts attention from more meaningful environmental risks, both unrelated and related to GMOs.

At the other end of the spectrum is the view that deployment should only be delayed where adverse consequences have been demonstrated. This approach provides the advantage of insisting on scientifically based criteria. However, it has some significant disadvantages. First, it seriously underestimates the complexity of scaling across levels of biological organization, from small areas to landscapes, and from time scales based on rapid bioassays within grant cycles, to times scales based on ecological and evolutionary processes. There is nothing scientific about ignoring how system processes change as you scale up, as there are many precedents in meteorology, soil erosion, engineering, and biology. Second, the argument that risks should be considered scientifically based only once they have been 'demonstrated' removes the proactive element of risk assessment, and shifts the emphasis to remediation, which is far more difficult. This reactive approach has cost agrichemical companies severely, which is why they now invest substantial resources to prevent pesticide resistance. Finally, the argument that all risks can be classified as either 'demonstrated' or 'conjectural' creates a false dichotomy. It ignores the broad range of anticipated problems that may be considered ' realistic'. I believe we can define 'realistic risk' on the basis of two criteria (Raffa et al. 1997): 1) The existence of relevant precedents that suggest likely outcomes; 2) A proposed mechanism that can be delineated on the basis of biologically verified processes. I will focus on two anticipated responses to pest resistant transgenes in tree plantations, evolution of resistant biotypes, and alteration of complex ecosystem processes.

BIOTYPE EVOLUTION: RISKS AND MANAGEMENT

Biotype evolution is the emergence of new pest races that are no longer susceptible to a previously effective control tactic (Roush 1987; 1997; Tabashnik 1994). The underlying mechanisms are well understood, at several levels of biological organization. At the population level, biotype evolution is simply natural selection proceeding in an accelerated and directed fashion. A few individuals possessing fortuitous mutations survive, reproduce, and ultimately occur at disproportionately high frequencies. Biotype evolution is not a rare phenomenon, but is rather an inevitable consequence of any selection pressure that is applied continuously, uniformly, and at sufficient intensity to cause high mortality (Gould 1988; Raffa 1989; Tiedje et al. 1989; Abbott 1994; Seidler and Levin 1994; Timmons et al. 1995;1996; van Embden 1999). Biotype evolution has occurred against all categories of pesticides, and also against resistant cultivars, biological control agents, and cultural manipulations (Raffa 1989). It is prevalent among all taxa of insects, pathogens, and weeds. The physiological and biochemical mechanisms are likewise well understood. In the case of insects, these mechanisms include altered behavior, detoxification, excretion, impermeability, and target site insensitivity.

The consequences of biotype evolution range from loss of efficacy to additional secondary effects. In most cases, loss of efficacy is the major and perhaps only significant consequence. Lost efficacy poses a substantial risk to the producer. Discovery, development, registration, and marketing of new pest control chemicals and transgenes are expensive processes. Corporations now invest heavily in biotype prevention tactics throughout all stages of agrichemical development to avoid these losses.

Effects that extend beyond reduced efficacy are of more concern from an environmental perspective. These include impacts on other resource managers, altered insect behavior, cross resistance to other pesticides, and cross resistance to natural plant defenses (Heinrichs and Mochida 1984, Fry 1989, Hilbeck et al. 1998, Johnson and Gould 1992, Rebollartellez et al. 1994). The microbial insecticide *Bacillus thuringiensis* is currently the most widely used insect control agent in forestry. It is also widely used in tree fruit production. Its acceptance arises from a combination of efficacy, economic, and environmental attributes. Bt is sprayed on an as-needed basis only, which greatly diminishes the likelihood of biotype evolution. In contrast, uniform and continuous expression in trees could more rapidly select for resistant insects, which in turn could reduce the efficacy of an environmentally compatible tool used in other cropping systems. There is substantial overlap in the species of insects that feed in these systems. An additional effect that needs to be considered is the possibility that resistant biotypes will have more damaging behavior than the original genotypes. Examples of altered behavior come from agroecosystems to which pesticides have been applied. Another significant threat of biotype evolution is cross-resistance. Resistance to one chemical class often confers resistance to widely unrelated compounds. An example occurred with the introduction of the synthetic pyrethroids. Although these materials were highly effective against lab and most field populations, they were almost immediately ineffective in certain regions. The pattern soon became obvious. Areas in which high levels of the organochlorine DDT had been applied harbored biotypes resistant to pyrethroids. These compounds are structurally dissimilar, but insect alteration of sodium channels conferred resistance against DDT, and did likewise against pyrethrum. Pyrethrum is a naturally occurring botanical, so from the insect's standpoint, DDT is just a recent human variation on an ancient angiosperm theme. This raises the possibility that genetically engineered products might not only select for cross resistance to other pesticides, but to naturally occurring plant defenses as well. This has already been observed with synthetic pesticides (Fry 1989).

The conditions that foster evolution of resistance biotypes are relatively well understood. In particular, the rate of evolution of pesticide resistance depends more on the pattern of application than the mode of action. Patterns of expression that are uniform, large-scale, unidirectional, and continuous select more rapidly for resistance than do intermittent patterns. If there has been one achievement of pest management that ranks above all others over the last 30 years, it is the replacement of calendar applications with targeted applications triggered by specific pest densities that surpass carefully defined economic thresholds. This transition has provided an overall reduction in pesticides, increased profits to the grower, improved pest control, and greater compatibility with diverse management tactics such as biological control, mating disruption, and cultural manipulations. Thus, a particular technology, such as constitutive transgene expression in plants, may simultaneously represent a modern innovation at one level of scale, and an archaic throwback at another. Conversely, many of the solutions to problems identified by ecologists can best be solved by molecular biologists, or by molecular biologist – ecologist teams.

A number of tactics are available to manage biotype evolution, and many of these can be readily transferred to genetically modified plants. These tactics arose both from agriculture and our understanding of naturally coevolved stable plant – insect interactions. First, we should identify those systems in which biotype evolution appears particularly likely, and avoid them. Expression of transgenic traits is more problematic with trees than annual crops, because of their long rotation times relative to insects. Many tree production systems provide crop to pest generation ratios an order-of-magnitude above that required to elicit pesticide resistance (Georghiou and Saito 1983). Thus, rapid rotation systems such as *Populus* and *Eucalyptus* are less at risk than are slower systems such as Douglas-fir. Second, biotypes are less likely to evolve when expression is limited in time. This is a key lesson obtained of the transition from calendar to density-triggered applications. One approach to simulating this is through wound-inducible expression. This is one of the most important means by which long-lived trees maintain stable defenses against herbivores and pathogens. Other approaches include limiting expression to certain periods of the growing season and to certain age categories. Various insect species show clear patterns of seasonal abundance, as well as association with particular age categories. Trees differentially allocate defenses according these abundance patterns. Third, expression is most stable when it is limited in space. Spatial expression can vary among plant tissues, as is common in tree-resistance mechanisms, and also among trees. This tactic has already been employed with transgenic cotton and corn, in which fixed percentages of the 'transgenic' seed are in fact not transgenes. Superimposing genetic diversity onto transgene expression adds another layer of protection. Hybrid poplars seem particularly amenable to this approach. Whether or not clones are transgenic, this is a valuable safeguard against new insect and disease races and species. Fourth, the transgene should be compatible with other control methods. This helps maintain a diverse and opposing array of selective pressures. Natural systems often pose insects with conflicting alternatives. For example, aphids escape predation by releasing alarm pheromones when predators are near. Some wild plants react to aphid feeding by producing aphid alarm pheromone, which causes the aphids to drop from the plant. Imagine insects that became immune to this defense: if they ignored alarm pheromones they would become more susceptible to predators. Fifth, application of potentiators that specifically interfere with resistance mechanisms can greatly prolong activity. For example, insecticide resistance is often due to elevated detoxification enzyme titers. Inhibitors of P450's, such as piperonyl butoxide, interfere with detoxification, and so can render resistant individuals susceptible. Again turning to coevolved systems as a model, some plants produce both insecticides and synergists. We have recently reported synergy of *Bacillus thuringiensis* by linear aminopolyol zwittermicin A, an antibiotic from soil bacteria. A sixth strategy is continued monitoring of resistance. As incipient resistance is identified, its mechanism and mode of inheritance are characterized, and specific counter measures can be employed.

Experience with pesticides also suggests what is unlikely to work. First, it seems reasonable that interrupted use of a pesticide will allow resistant populations to return to their original gene frequencies. The underlying assumption is that resistance characters are inherently disadvantageous and will be selected against in the absence of the pesticide. Unfortunately, this has proven to not always be the case (Brattsten et al. 1986; Roush 1987, 1997; Gould 1988). Second, the strategy that multiple genes of Bt are available, and so we can stay ahead of resistance by deploying new ones as resistances evolve is not supported by experience with other pesticides. Thus, it is no surprise that pest management specialists are not enthused about this approach. Insects have shown remarkable ability to develop cross resistance against very distant chemical groups (Georghiou and Saito1983; Brattsten et al. 1986; Mullercohn et al. 1996). Cross resistances have occurred among many classes of pesticides, and by several mechanisms. Given the evolutionary history of insects in contending with millions of phytochemical combinations over hundreds of millions of years, placing our confidence in a few varieties of Bt does not seem the best option.

ALTERATION OF COMPLEX ECOSYSTEM PROCESSES

The issue of whether transgenic plants could exert serious environmental effects hinges greatly on whether there is gene flow into native plants. If gene expression is limited to planted trees and mechanisms for preventing introgression are employed, then adverse environmental effects are likely to be limited and subject to remediation. However, if gene flow is likely, risk assessment needs to be tailored accordingly.

The issue of potential gene escape has generated much debate among geneticists (e.g., Regal 1993; Linder and Schmitt 1995; Strauss et al. 1995; Timmons et al. 1995; Karieva et al. 1996; Paoletti and Pimentel 1996; Parker and Karieva 1996). However, there is general agreement there is some gene flow from cultivated to native and feral plants. Some potential mechanisms include hybridization, dissemination of vegetative material, and vectors. Strauss et al. (1995) concluded "gene flow within and among tree populations is usually extensive, which makes the probability of transgene escape from plantations high (Adams 1992, Raybould and Gray 1993)". They based their conclusions on "high rates of gene dispersal by pollen and seed, and proximity of engineered trees to natural or feral stands on interfertile species."

Proposed adverse environmental effects include enhanced weediness, reduced biodiversity, and alteration of ecosystem processes. Moreover, Parker and Karieva (1996) identified pest resistance as the form of transgene property most likely to cause such problems. The issue of enhanced weediness has received much attention, and so will not be addressed here. Likewise, the issue of biodiversity has been discussed in detail elsewhere, and so time does not allow me to add to this. I will focus instead on ecosystem processes. In particular, I will focus on examples where prior experience with pesticides and new cultivars have resulted in exacerbated pest problems. These include direct and indirect effects on natural enemies, and release of competitors.

The extent to which transgenic trees will directly affect predators depends on the gene product. In particular stable materials are more likely to be biomagnified across trophic levels. For example, biomagnifcation is not known to occur with Bt. As we project into the future, three considerations should be considered. First, herbivores usually evolve resistance to xenobiotics more rapidly than do predators. This appears to relate to their coevolutionary history with plant defense chemicals. Second, even if a xenobiotic has equivalent toxicity to an herbivore and its predator, it will have a greater effect on predator than herbivore populations. This has been demonstrated in numerous mathematical models, and relates to issues of prey finding, prey handling, and differences in reproductive capacity. Third, most predators are generalists, so control methods that reduce predators of target pests can cause population increases of non-pest species. Relationships become more complicated when parasitic insects are considered. In general, parasites develop better in healthy than weakened host insects (Visser 1994; Havill and Raffa 2000). So anything that reduces herbivore vigor is likely to result in parasite death prior to its completing development. In this regard, transgenic plantings can become sinks for parasite populations (Johnson and Gould 1992). Parasites tend to be have more narrow host ranges than predators, but few are true specialists. Thus the possibility of secondary pest flare-up remains, as is commonly seen with sprayed toxins.

Emergence of secondary pests is a common and serious problem when insecticides or resistant cultivars are deployed. For example, mite outbreaks often follow applications of pyrethroids, and historically followed application of DDT. The most serious outbreaks of spruce spider mite followed aerial application of DDT against spruce budworm. Likewise, introductions of new cultivars have resulted in the emergence of previously unimportant pests. A new cultivar that was bred for pest resistance sometimes reduces the pest species but frees others from competition. In other cases, breeding for unrelated properties inadvertently enhanced the plant's susceptibility or nutritional suitability to another insect. Again, natural systems demonstrate that these are not rare examples. For almost every phytochemical that has been shown to confer resistance against most insects, there are also other species that use this so-called defensive compound for nutrition, defense, or communication. The seriousness of this problem again depends on whether there is gene flow from transgenic plants into wild and feral populations.

RISK ASSESSMENT: MECHANISMS AND PRECEDENTS

As stated above, risk assessment can be both proactive and realistic when it is founded on verified mechanisms and relevant precedent. I have described several putative mechanisms, based on known features of insect physiology, behavior, and population ecology. I have also used experiences with pesticides as a precedent. But not all biologists agree that this is an adequate precedent, and so competing models have been proposed for risk assessment. I would like to comment on some of the most common models proposed for evaluating pest-resistant plants.

Pesticide registration as a model for pest resistant transgenes has several advantages. First it focuses attention on the gene product. It can be tested like other compounds for acute and chronic toxicity to humans, for effects on beneficial organisms, and alone or in combination with phytochemicals. Such tests are expensive, but the methods are straightforward, experimental conditions can be shielded from investigator bias, and the results can be interpreted relatively easily. I do not mean to minimize the difficulty of conducting toxicological studies, and recognize that there are sometimes peculiar dose – response relationships, complex immunological interactions, and unpredictable multi-chemical interactions. But corporations welcome this approach because it provides them with a clear target, and they can draw on years of experience with agrichemicals, pharmaceuticals, industrial reagents, and cosmetics. Researchers in all sectors want to be sure that materials they introduce into the environment are safe. Whether this approach is adequate depends largely on whether transgenes have the potential to become established in wild populations. If sterility is incorporated into the genome and vegetative parts are contained, there are no apparent risks beyond those associated with any environmental input. If those conditions are not met, however, the pesticide analogy is applicable but inadequate. Pesticide inputs can be halted at any time, and materials with excessively long residual periods are banned. This is a valuable aspect of pesticides, as compounds that had been approved for many decades commonly lose their certification as new toxicological problems are discovered.

Transgenic plants are often compared to plants bred by traditional methods. This analogy has some value in that it recognizes that environmental risks of transgenes apply to all monocultures, regardless of how the genome was derived. But the comparison is sometimes taken further to emphasize the added advantage of genes being introduced in a targeted rather than random fashion. From an efficacy standpoint that is indeed a major benefit to genetic engineering. But when it's extrapolated to environmental risk it reverses the product not process principle—suddenly the process is the basis for justification. At the scale of pest management, the only thing transgenic and traditionally bred crops have in common is the process, i.e., deploying the toxin through plants. It is also sometimes argued that a single gene would have less effect than the multiple rearrangements that take place through traditional breeding. However there is little evidence to support this assumption, and certainly biological bases for being skeptical. First, single genes often have dramatic effects, as in the cases of many human diseases, pesticide resistant insects and pathogens, and cultivar-resistant pathogens. Second, the genes that can be achieved through traditional breeding are limited to the pool of genes from the plant's evolutionary history. This is a strong argument in favor of the efficacy and utility of genetic engineering, but not anticipated environmental safety. Our most severe pest problems have occurred in noncoadapted systems. Third, this analogy does not consider either pleiotropic effects, or gene by environment interactions. Yet we know these can be extremely important in determining how insect – plant interactions and insect populations behave. So resistance breeding is a useful but inadequate precedent.

A third regulatory area with applicability to transgenic pest resistance is the planned introduction of beneficial organisms. First it is consistent with the *product not process* philosophy. The 1987 National Academy of Sciences states introducing genetically modified organisms "poses no risks different from the introduction of unmodified organisms." Note they did not say "less than"; they said not "different from." To argue that GMOs should be treated differently from other introduced organisms would be a radical departure from the product not process guideline. Second, GMOs and biological control agents are both selected because of specific desirable properties. Third, risk assessment of biocontrol agents places a premium on ecological considerations, specifically on how these agents will affect other components of the ecosystem. This is precisely the area where risk assessment of GMOs has lagged. The biocontrol analogy also has a limitation. Biological control agents are intended to become self sustaining. In the case of transgenic trees, this would be an unintended consequence. Treating GMOs as we do putative biocontrol agents does not pose insurmountable obstacles. Literally hundreds of biocontrol agents have been approved for release. Moreover it is disingenuous for proponents of GMOs to argue that they have been singled out for unprecedented scrutiny, and at the same time object to risk assessment standards applied to other sectors for many decades. It might be argued that the standards applied to biological control agents are too lax, as some adverse effects have occurred. However, most such problems have arisen either from organisms that were released privately, or were released many years ago under standards less well informed than those applied at present.

CONCLUSIONS

Risk assessment of pest resistant trees is still in its infancy. We can identify certain risks, some of which would exert environmental harm, others which would squander valuable transgenes. The extent to which various risk-assessment approaches apply depends on the extent to which gene flow can be eliminated. Where sterility is introduced and vegetative materials are contained, procedures for pesticide evaluation are most applicable. Where either ingredient is missing, the most applicable standard is the planned introduction of putatively beneficial organisms. Several obstacles impede scientifically based risk assessment. These include 1) inconsistent application of the *product not process* principle; b) extrapolation across multiple levels of biological organization, spatial scales and time frames without verifying the underlying assumption that system processes remain uniform; c) insufficient attention to general principles where specific information is not yet available; and d) systematic biases in research support that favor a risk analysis process based on precise but simplified conditions over complex but more realistic interactions.

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Ecological Considerations for Potentially Sustainable Plantation Forests

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ABSTRACT

Essential forest ecosystem components and processes must be maintained at all levels of forest management intensity—from 'wilderness' and ecological reserves, from which no trees are removed for commercial purposes, to 'fiber farm' plantations that are managed as intensively as cropping systems. Minimum requirements for sustainable forest ecosystems include viable tree propagules; system capacity to provide aeration and support for roots; water supply; and nutrient supply for flora and fauna, including functional ecosystem components and processes required for energy and nutrient dynamics; propagules and habitats for mycorrhiza-forming fungi; and ecosystem resilience, resistance or protection from epidemic or damaging tree pathogens—insects, animals, or microbes. On watershed and landscape scales sustaining viable populations of native organisms is important. For some ecosystems, protection from, or resilience to, wind, fire, or other disturbances may be needed.

This framework for sustainable forests must include definitions of system boundaries and interchanges and interactions with adjacent systems, system components and processes, inputs to the system, and outputs. Inherent in such a view would be assumptions about availability of energy sources for system dynamics and disturbances, and climatic setting of each system. And, to be truly inclusive, frameworks for sustainability must include considerations of interactions between forests and human communities within and dependent on them. To be relevant to assessing ecosystem sustainability, ecological research must include humans and human systems along with forest ecosystems at all scales.

These criteria of sustainable forest ecosystems provide a convenient conceptual framework for examining the potential for introduced species and genetically modified organisms (GMOs) to have unanticipated ecological impacts at stand or landscape levels of resolution. While there is considerable experience with introductions of exotic tree plantations (e.g., radiata pine), inadequate research has been conducted to test long-term hypotheses about the impacts of introducing GMOs into forest ecosystems. However, this conceptual framework suggests that critical analysis might be focused on such areas as interspecific organism interactions (e.g., plant–plant, plant–animal, plant–insect); pollen drift contributing to sexually mediated gene modification and distribution; vegetative or clonal population expansion of GMOs; GMO-mediated effects on ecosystem components and processes that alter energy or nutrient dynamics; and GMO-related changes in ecosystem resilience and resistance. All considerations must be made at stand, forest, watershed, landscape, and regional scales.

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We humans manage many types of forests for many products and values, ranging from firewood and structural materials to recreational and spiritual values. For this discussion we're considering forests that, in general, are forest tree plantations that are much simpler and 'more organized' than are traditionally wildland forests. We focus attention and examples and discussion on temperate and boreal forests. And, we include emphasis on potentials of transgenic trees as components of these forest plantations.

For many, considerations of forest management begin at and focus on the stand level, a level beyond individual trees but less encompassing than an entire “forest”.

In many regions of the world forests and tree plantations exist as *tessera*—small parts—in landscapes that are mosaics of many land uses—human settlements, roads, farmlands, plantations, and wildland forests. This is the case in the McKenzie River Valley in the Cascades Mountains east of Eugene, Oregon, USA, in Queensland, Australia, and in southern Sweden (Figure 1).

Our main focus for this brief discussion is single-species, intensively managed tree plantations. Considerations of using intensively managed trees, in whatever form, raise, in the minds of some, concerns about ‘alien’ organisms in our forests. But, of course, we already have many aliens in our forests, e.g., many weeds, some birds, insects, and other organisms.

Most of the exotic species in our forests today, with some exceptions (kudzu, gorse, Scotch broom) are not so very visually intrusive. Transgenic plantations amongst forests might be otherwise. Many forests and forest tree plantations are intensively managed, with thinning, competition control and other stand tending procedures. Will intensive tree plantations in the forests of today be much different than what we now have? Those are the issues we confront here.

Figure 1. McKenzie River Valley, Oregon (above), and Queensland, Australia, landscapes.

Intensively managed plantations already exist in many places in the world, e.g., pine plantations as parts of mosaics of deciduous forest landscapes in the southeastern United States, parts of landscapes in Sweden, New Zealand, Australia, and Chile. In Scotland, New Zealand, Australia, and elsewhere, there are vast areas of exotic plantations, intensively managed and used for a variety of purposes. These plantations provide wildlife habitats and watershed protection. Among considerations of such plantations, at least in some places, are the visual quality values of geometric shapes of plantations, with numerous attendant aesthetic and ecological implications. In England and Scotland landscape architects have worked with foresters to ‘reshape’ planted forests to fit more aesthetically into landscapes. Plantation edges that are more amoeba-like than linear may be not only more aesthetically pleasing, but will provide more total edge and more potentials for ecological interactions with adjacent forests or other land cover.

In contrast to relatively small plantations fitted into landscapes, there are, of course, vast landscapes of planted and intensively managed forests, such as those of *Pinus radiata* in New Zealand, and *Pinus patula* in Swaziland. Some of these planted forests dominate landscapes for thousands of hectares and provide ecological conditions that are quite different from native forests or from previous agricultural land uses.

And, there are also vast expanses of mostly single-species native/natural forests, such as those of Douglas-fir and lodgepole pine that originated after large fires in the Pacific Northwest and intermountain regions of the United States and Canada. Foresters and forest scientists have long worked in such forests in Europe, Russia and North America, so we have significant knowledge of the ecology of large, single-species forests, some managed and some relatively wild.

Ecological considerations of plantations are important at several scales, from stand, to watershed, landscape and region to country and, perhaps, continental expanses. For considering ecological implications of plantation forests, including those of transgenic trees, the ecosystem concept provides a useful framework of reference. This concept has been used to assist in understanding much of our current knowledge of forest ecology, at many scales, from stand to landscape. This concept is oft depicted as some sort of model, whether as in a simple sketch or as some relatively complex mathematical set of equations and relationships in a computer-based model.

As Hamish Kimmins has written in his *Forest Ecology* textbook, it's useful to consider ecosystems, whatever the scale and setting, with these elements: boundaries, components (physical and biological), structure, processes of transfers of energy and matter, interactions and interdependencies, and, dynamics over time.

As considerations of ecosystems require more details, models, of whatever form, become more complex. Definitions, evaluations, and estimates of all model elements add complexity and details, for example, of transfers of nitrogen from soils to tree roots, or movements of nitrate ions into stream waters. In context with a larger forest and landscape, there will be many exchanges of organisms, matter and energy among planted forests and adjacent ecosystems, including aquatic systems.

For example, where transgenic trees grow in close proximity to native populations of the same genus or species, such as some plantings of hybrid poplars, there exists potential for gene flow to and from adjacent trees. Geneticists working with potential transgenic trees have made many thorough and careful considerations of this potential. Use of infertile trees, as is being done now in some experimental and production plantations, is one method of limiting interactions. In addition to potential gene flows, the issues of adjacency and edges have numerous implications for movements of organisms and propagules, plant, animal and microbial, between plantation trees and forests or agricultural lands.

In arid central Oregon, USA, thousands of hectares of hybrid poplars grow in a landscape where limited populations of native cottonwoods grow in moist stream courses, so interchanges of organisms and organic matter are likely. In the lower Columbia River Basin, northwest of Portland, Oregon, USA, there have for decades been hybrid poplar plantations on former agricultural lands, intermixed with numerous other land covers and uses.

In other settings, such as the tussock grass covered highlands of the Clarence River Valley and Cragieburn regions of South Island, New Zealand, reforestation/afforestation has been implemented with a variety of exotic conifer species, including, inter alia, *Pinus contorta* (Figure 2). One issue that New Zealand foresters and other land managers have confronted is the "weediness" of *P. contorta,* seeds of which have spread beyond intended planted areas and have grown into troublesome trees in places where they are not wanted.

At another scale of forest ecosystem consideration, forest structure is very important, as it creates and influences habitats for numerous organisms, plant, animal, and microbial. The complex structure of a native podocarp forest with understory tree ferns on North Island, New Zealand, is in sharp contrast to the relatively simple structure of a 42-year-old *Pinus radiata* forest (Figure 3).

Figure 2. Pinus contorta, Cragieburn, New Zealand.

Diseases of trees and forests, fungal or otherwise (see Figure 4, mistletoe on *Pinus ponderosa* in central Oregon), must be considered in potential interactions among plantations and adjacent forests. Insects and other arthropods also interact in many ways with trees and forests, and perform essential, as well as detrimental functions. For example, early stages of disintegration and decomposition of many plant residues are caused by arthropods.

Scales for considerations of structure, diseases and insects, and other forest ecosystem components and processes may range from landscape and watershed to stand, individual tree rooting zone, rhizospheres and mycor-

Figure 3. Forest structure: (a) podocarps and (b) 42-yr-old Pinus radiata plantation.

Figure 4. Mistletoe in Pinus ponderosa, central Oregon, USA.

rhizae, and microscopic soil organic matter and clay particles.

Following are examples of some more detailed scales of considerations from our experiences with forest soils. Similar examples should be developed for all important forest components and processes. For example, Tommerås et al. in discussing potential implications of transgenic *Picea abies* in Norwegian forests, created this general scheme of possible implications of introduced fungus-resistant trees (Figure 5). Of course, such resistance would/could likely exist in tissues of residues in forest floors and in roots—which might influence decomposition processes both qualitatively and quantitatively, and, also, might affect mycorrhizae.

For these detailed, process-level considerations, conceptual models can also be useful. Here's simple 'model' of interactions of forest vegetation with soils (Figure 6).

Of course, the depicted relationships are much more complex and "chaotic" than represented, and are very difficult to study and define individually.

Soil biota and the processes and ecosystem properties that they control and influence are examples of the extreme complexity of soil-vegetation systems and of other sub systems of forests and plantations. Modifications in the chemical or structural composition of wood or other plant tissues will likely affect the decomposer communities and subsequently also the decomposition processes. However, it is also most likely that these modified plant tissues will fall within the range of existing substrate for decomposer organisms—they are not likely to be 'alien' to the systems (Figure 7).

Mixed species forests, such as those in Sweden with birches and pines, could be models for considering using mixtures of species in plantations of transgenic trees. The relative merits of mixed species plantations have been thoroughly discussed in the forestry literature. Such plantations provide diversity in many ecosystem characteristics e.g., niches for epiphytes; ground flora, and for fauna of all sizes; microclimate; hydrology; bio-

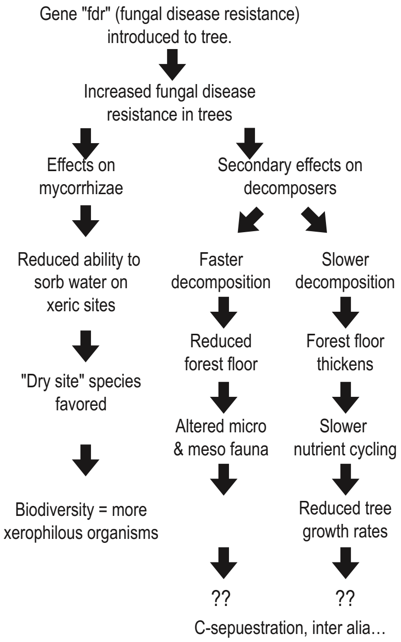

Figure 5. Potential effects on soils of disease-resistant trees (from Tommerås et al.).

geochemistry; soil fauna and microbes. Considerations of plantations and species homogeneity discussed by Peterken include physiognomy; composition; structure; age structure; community patterns; patterns of open spaces; and, site properties and processes.

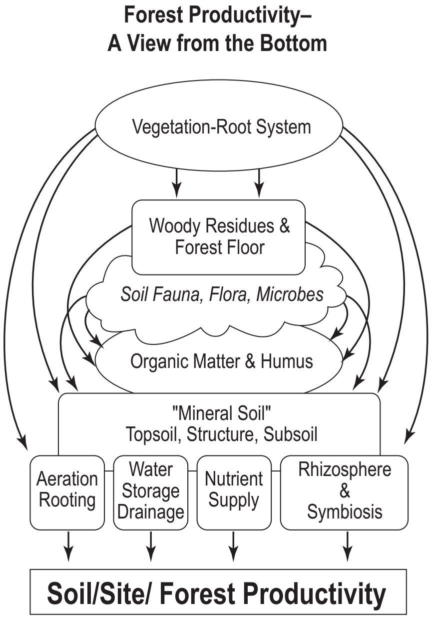

Figure 6. Soils and forest productivity.

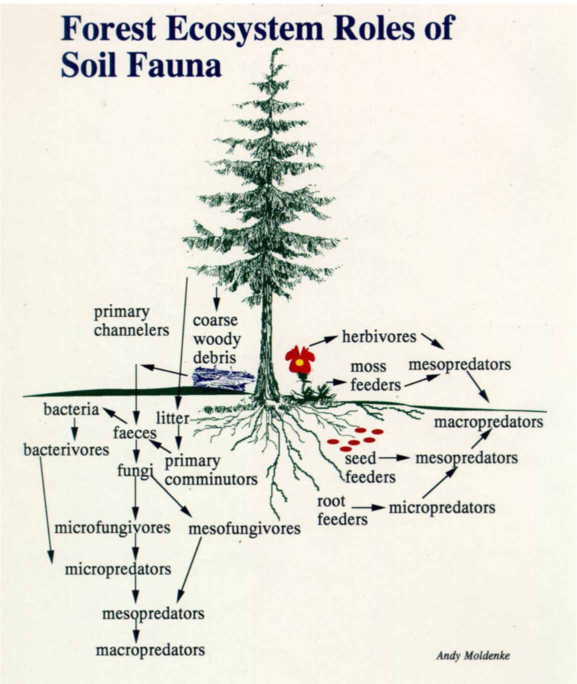

Figure 7. Roles of soil fauna (by Dr. Andy Moldenke).

CONCLUSIONS

Our cultures and daily lives include dependence on millions of hectares of intensively managed and manipulated lands with highly simplified and cultured vegetation, including agricultural food crops, grazing lands, vineyards, fruit and nut orchards, and forest tree plantations grown for wood and fiber. Intensively managed plantation forests and agricultural-like tree farms are currently providing wood fiber, and other forest ecosystem 'services', e.g., soil protection from erosive forces in many places, soil building with *Pinus radiata* on sand dunes in New Zealand, and on abandoned, degraded agricultural and grazing lands in central Chile.

For generations intensively managed, cultured crops and lands have coexisted with native vegetation ecosystems and human habitations, as exemplified by the historic landscapes of Sweden and elsewhere.

We suggest the following for further thinking about ecological implications of plantations of forest trees, including transgenic trees:

1. Recognition of scale—stand-watershed/landscape-region—is important; and, scale "down" from stand to tree to soil particle and root tip and microorganism.

2. An "ecosystem concept", at numerous levels of detail is useful to consider dynamics of matter, energy and organisms, and to, for example help frame and develop working, testable hypotheses about, e.g.,

    - interspecific organism interactions (plant-plant, plant-animal, plant-insect

    - effects of single-species systems on ecosystem components and processes, which alter energy or nutrient dynamics, e.g., alteration of microorganism-arthropod-bird food webs

    - changes in resilience and resistance of ecosystems in relation to disturbances.

Finally, in all these relatively narrowly focused technical and ecological considerations, we must remember the larger context in which we think about trees and forests. We assert that our overall goal as forest scientists is to contribute to potential sustainability of human communities in the face of expanding populations and limits of ecosystems' processes, services and resiliences. We're working to somehow "design the human enterprise to fit nature" (as David Orr has written). We have many current examples of forestry as a human enterprise fitting rather well into "nature", for example, landscapes of agricultural, forested and human-occupied lands in Queensland, Australia, many parts of Sweden, Norway, and Finland, and Minnesota, USA. We must remember that our ultimate concerns are not for today's genetic or ecosystem science, but for our grandchildren and great-grandchildren and the next seven generations.

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GE Trees: Proceed only with Caution

Faith T. Campbell
Rachel Asante-Owusu

ABSTRACT

Environmentalists are concerned about potential negative impacts of genetic engineering of trees. Among our concerns are 1) novel genetic material escaping into wild relatives; 2) impacts of inserted pesticidal properties on forest food webs and ecosystem processes; 3) repercussions of pests' developing resistance to pesticidal properties; 4) enhanced 'weediness' of the transgenic organism or its relatives in natural systems; 5) impacts of altered lignin content on forest food webs and ecosystems; and 6) negative environmental impacts from application of technologies intended to manage the GE organism—including induced sterility and increased use of herbicides.

The proponents and regulators bear the responsibility for carrying out empirical research to minimize uncertainty surrounding these concerns. While no one can characterize the risks with precision, their potential magnitude and irreversibility argue for applying the Precautionary Principle.

Current regulatory programs lack a true scientific foundation because they rely too much on assumptions and subjective judgements rather than experimental data. These faults are exacerbated by the absence of true peer review and apparent conflicts of interest. GE organisms should be studied intensively by independent researchers before they are approved for commercial use.

Government, academia, and industry should devote equal effort to exploring alternative, more environmentally benign approaches to achieving the economic, social, and environmental goals that motivate genetic engineering experiments.

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Genetic modification offers the industrial forest sector potential for developments undreamed of 20 years ago. One of the main advantages is the cheaper production of wood fiber. However, the advantages of new technologies are often easily conceived while the costs are difficult to appreciate due to uncertainty, risk, and imperfect knowledge.

Many environmentalists are concerned about a wide range of potential negative impacts that could arise from genetic engineering of trees. At present, scientific knowledge does not allow precise definition of these risks. However, the history of introductions of exotic species demonstrates that novel phenotypes often behave in ways that were not predicted and that serious ecological effects can arise following very rare events (Royal Society of Canada 2001).

While some environmentalists might argue that the difficulty of predicting impacts warrants a prohibition on all genetic engineering of trees, we advance a less Draconian version of the Precautionary Principle. First, forestalling possible environmental damage is far superior to attempting a 'cleanup' after harm has occurred. Furthermore, it is irresponsible to proceed with commercial deployment of GE technology until scientific understanding of both forest ecosystems and the behavior of the genetically engineered organisms in nature is considerably improved. Finally, those proposing use of genetically engineered tree—and regulators charged with protecting the environment and public welfare—bear the responsibility for carrying out the empirical research needed to minimize uncertainties about the nature and extent of the possible risks and to identify effective ways to manage those risks that society decides to accept.

Building a truly scientific foundation for managing the risks associated with genetic engineering will require reform of both the regulatory structure and the science community. We need to provide greatly increased funds to independent scientists studying relevant aspects of forest ecology. Agency responsibilities must be changed to eliminate conflicts of interest. Regulators need to insist on peer-reviewed experimental data rather than assumptions and subjective judgements.

We call on all players—including corporations, academic scientists, public officials, and interested citizens—to put in the sustained effort needed to bring about this restructuring. We believe that all will benefit from enhanced protection of the environment, improved credibility, and a better quality of life.

ENVIRONMENTALISTS' CONCERNS

Environmentalists worry about possible negative impacts that could arise from genetic engineering of trees. Our concerns arise in part analogies with invasive species and a growing skepticism about regulators' foresight and willingness to act. Scientists working with the technology and regulators have sought to dampen these concerns by putting forward reasoned interpretations of scientific theory. Rarely, however, can either side ground its position in empirical research. The best way to resolve the disputes over the risks is to conduct research on the points of contention.

Possible Risks Requiring Study

Environmentalists want further study of

- the extent to which inserted genetic material might escape from the engineered organism into wild relatives and the repercussions of such introgression
- impacts on forest food webs and ecosystem processes resulting from inserted pesticidal properties
- repercussions of pests' developing resistance to inserted pesticidal properties
- the risk that transgenic organism or their relatives might be more "weedy", especially in natural systems
- potential impacts on forest food webs and ecosystem processes resulting from other types of genetic manipulation, for example, of lignin content
- possible negative environmental impacts from application of various technologies intended to manage the GE organism—including induced sterility and increased use of herbicides.

Questions about the Underlying Rationales

Research should also examine the underlying rationales for utilizing genetic engineering technology in forestry. For example, will there be shortages in the future for the types of wood products supplied by fast-growing plantations? New Zealand expects to double its harvest from plantations by 2020 (ForestPacRim: NZ Forest Minister addresses Forestry conference: Date: 10/5/2000 7:02:23 AM Eastern Daylight Time). In Brazil, some plantations of improved *Eucalyptus* already produce 90 to 100 m^3 per hectare per year. A subsidiary of Champion International expects to begin producing 2.6 million tons of chips a year by 2004 on new plantations totaling 100,000 ha. Fast-growing plantations of improved *Eucalyptus* are already in the ground or planned for other South American countries (USDA Forest Service 2001). Recent analysis by World Wildlife Fund and the World Bank Alliance has shown that 20% of the world's total forest estates is sufficient to supply current and future generations' industrial roundwood needs if proper management systems are put in place [The Forest Industry in the 21st Century. WWF International March 2001].

Second, can alternative technologies reduce demand for GE wood fiber? Victor and Ausubel (2000) point out that advances in milling and processing technologies could result in global demand being stabilized at around 2 billion cubic meters per year by 2050 (current demand is about 1.6 billion cubic meters). A number of annual plants, including hemp *Cannabis sativa* L. and kenaf *Hibiscus cannabinus* L., have proven qualities as paper crops; among other advantages, they lack lignins. Various agricultural wastes can be utilized in making paper. An increased commitment to recycling and demand reduction programs could also have an impact. One expert, Rick Meis of TreeCycle Inc. (personal communication) estimates that utilization of agricultural wastes and demand reduction could together cut U.S. demand for virgin fiber by 20%. Finally, innovative use of enzymes in wood-fiber processing (ForestPacRim: NZ Forest Minister addresses Forestry conference: Date: 10/5/2000 7:02:23 AM Eastern Daylight Time) might better solve the environmental and energy costs of processing lignin from tree fibers.

Third, does intensive management of plantations—whether composed of genetically engineered or conventionally bred trees—actually result in increased protection for natural forests? At a global level, forest loss and degradation are being driven by two failures: of the market and policy makers to value properly the whole range of forest goods and services; and of authorities to curb illegal logging (up to 50% of the world's timber is harvested illegally). Other factors include forest fires and conversion to agriculture. In the United States, it is questionable whether wood products corporations would retain ownership of large landholdings from which they were not harvesting timber. If they sold the land, to what use would buyers put it? Alternatively, corporations might expand profitable plantations to control a greater share of the market. Curbing deforestation requires complex strategies in which more efficient production of fiber plays only a small role.

Finally plantations of fast-growing trees are not an effective way to mitigate global warming. If natural forests are cut down to make room for the plantations, a huge pulse of CO_2 is emitted when the forest is cleared. Scientists agree that less than 30% of the carbon removed from a forest by logging actually ends up stored long term in wood products. The other 70% is oxidized into CO_2 and emitted, partly through the burning of logging slash and mill wastes, and partly through the decay of the slash that does not burn. The time required for a fast-growing replacement plantation to recapture the lost carbon ranges from perhaps 30 years, when the original forest was a young, natural southeastern grove, to over 300 years when it was Pacific Northwest old growth.

SPECIFIC ISSUES

Escape

The chance that any inserted genetic material from the engineered organism might escape into wild relatives and change the genome of native trees troubles 'purist' environmentalists. The authors can envision good reasons for deliberately altering the genome of a native tree species, primarily to help restore a species endangered by exotic pests. Other environmentalists might not accept even this rationale. However, the prospect of altering wild trees' genomes as an unintended consequence of the development of a commercial crop raises many red flags. This is true even if the changes are subtle, or take many decades or a century or more to reach a substantial proportion of the wild population.

It appears to us from the literature that there is a high likelihood that an inserted gene will escape. Scientists have measured substantial gene flow from a wide variety of wind-pollinated tree species (CEQ/OSTP). Studies of poplars by the TGERC at Oregon State University, reported by DiFazio et al. (1999), found 18% of seeds caught in traps were of hybrid origin. Up to 3.8% of seedlings sprouting in cleared plots had been fathered by male trees in the plantations. Other sources noting a likelihood of genetic leaks include a USDA-convened panel of experts on poplars (Strauss 1999), Raffa (1997), and Charest (1995).

There has been considerable discussion as to whether novel genes would survive in wild populations. Many scientists believe that to persist, the novel genes must convey traits that give trees a competitive advantage in the wild. Several scientists doubt herbicide tolerance or insect resistance will convey such benefits; according to the theory, these genes would probably die out quickly. Other types of traits—e.g., height, diameter growth, and disease resistance—are thought more likely to convey fitness and persist (CEQ/OSTP). DiFazio et al. (1999) found that the seedlings bearing genetic material from the plantation trees established in greater numbers than expected, grew faster, and had higher survival over the winter. The authors conclude that the major factors that would limit the spread of human-altered genetic material in poplars are the fact that a very low percentage of poplar seedlings can establish in the wild (because of the seedlings' inability to compete with most vegetation) and the dilution of the novel genetic material by the sheer quantity of heavily flowering wild trees. However, the extent to which progeny containing GE traits might establish and spread needs to be resolved by long-term empirical studies before commercial use of GE trees can be approved (CEQ/OSTP). These experiments must examine each specific engineered line, not just rely on generalizations drawn from study of traditionally bred hybrids (Royal Society 2001).

Truly preventing genetic leaks requires the reproductive isolation of the GE plant. Achieving this isolation has been challenging for agronomic crops, and we believe it will be more difficult with regard to trees—especially when the species being modified is native. All possible isolation techniques, ranging from the practices now used to control pollination of hybrid poplars to such new techniques as genetically induced sterility, must be tested—for the full length of the proposed growing period—to ensure they meet the stringent standards appropriate for managing GE trees (CEQ/OSTP). Achieving reproductive isolation might be more difficult as regards other types of trees, such as pines (Charest 1995).

Pesticidal Properties

Environmentalists worry that inserted pesticidal properties could have highly damaging effects on forest food webs and ecosystem processes. According to Raffa (1989), all tissues of all tree species are exploited by a variety of insects in nature. These forest insects are important components of complex food webs that are poorly understood by scientists. These gaps in understanding, especially those involving interactions between trees and herbivorous insects, impede predictions of these effects.

Certainly, spraying of pesticides to manage insects in tree plantations has major impacts on non-target insect populations and on the many insect predators. However, changing to trees that exude their own pesticides might not be the only, or even best, solution to this problem.

Many scientists believe that GE trees with the ability to express pesticidal properties will cause less damage to nontarget organisms than does spraying of insecticides. However, this belief does not appear to be supported by empirical research. Furthermore, Raffa et al. (1997) say that alteration of multi-trophic processes is a 'realistic' risk from use of pesticide-expressing GE trees. The results could include reduced populations of predators, parasites, scavengers, pollinators, and endangered or valued species. The Royal Society of Canada (2001) found studies to be inconclusive as to the impacts of genetically engineered pesticidal properties on natural enemies. One complication focused on by the Royal Society is that some parasites rely on pollen or nectar when they are adults, raising the importance of evaluating impacts of the pesticidal agent in pollen. There has been little study of pollinators other than honeybees. Nor can scientists rule out impacts from wind-blown pollen—if it is ingested. As to soil organisms, the Royal Society (2001) expected *Bacillus thuringiensis* (Bt) exuded from roots or plant material in soil to elicit some response from the rhizozphere and soil microbial community—but it did not know whether these changes would be significant. In May 2001, the Ecological Society of America published its new position on genetically engineered organisms; one of the Society's principal concerns was the possibility of harm to non-target species, such as soil organisms, non-pest insects, birds and other animals (http://esa.sdsc.edu/statement0601.htm).

Lignin Manipulation

Lignin is essential to trees and their structure, although it must be removed from the cellulose for production of high quality paper. On the other hand, producers of biofuels wish to increase the lignin content. Little information is currently available as to how alterations in lignin content might affect feeding and populations of defoliators (lignin reduces the ability of herbivores to digest plant material) (Barriere and Argillier 1993). Such changes could also affect soil structure and fertility as lignin slows down plant decomposition and degradation by microbes (Reddy 1984).

Resistance

If insects develop resistance to inserted pesticidal properties, the repercussions could be profound (Raffa 1989). Of course, insects develop resistance to pesticides that are sprayed as well as—presumably—those exuded from plants. As far as we can determine, scientific data are currently inadequate to support an evaluation of whether resistance is likely to occur more or less rapidly in response to genetically expressed pesticides or similar chemicals in sprays. The Royal Society of Canada (2001) called for immediate establishment of meaningful resistance monitoring guidelines.

In general, the more widely a toxin is used, the greater the possibility that insects will develop resistance. Bt is already in widespread use across North America—as sprays and in GE crops. The U.S. Environmental Protection Agency (EPA) is responsible for balancing use of Bt in various forms and targeting various insect/crop combinations to minimize development of resistance. Might the agency decide at some point to impose a ceiling on uses of Bt in order to slow development of resistance?

A favored strategy to slow or minimize insects' developing resistance is creation of refuges—breeding sites for insects that have not been exposed to the specific chemical and thus have not faced evolutionary pressures to develop resistance. However, planting GE trees expressing Bt close to non-Bt trees in refuges would reduce the reproductive isolation of these separate genotypes and force greater dependence on other approaches to minimize genetic leaks. If the refuges were planted with poplars engineered to tolerate herbicides, that trait would further complicate management to prevent persistence and spread.

A second problem is determining how large such refuges should be and where they should be located relative to the Bt crop (e.g., embedded within the planting, or immediately alongside, or at some distance away). The EPA and USDA Animal and Plant Health Inspection Service (APHIS) are currently revising upward their standards for corn and cotton (see FIFRA SAP 2001)—demonstrating that the agencies' earlier rules were based more on assumptions than on empirical data.

Third is the difficulty of ensuring that these refuges are maintained by the forester in the face of countervailing pressures to maximize return. At present, the EPA is not certain that corn farmers actually maintain the pesticide-free refuges mandated by existing regulations governing Bt corn (EPA/USDA Workshop 1999). Until the EPA demonstrates an increased capacity to enforce its own rules, we think it is foolish for the agency to add the further complication that would be posed by Bt trees.

Raffa et al. (1997) found that some tree/insect relationships created situations in which it was too likely that insects would evolve resistance in response to a tree that exudes its own pesticide. These "too risky" groups included bark beetles and wood borers. Have other scientists studied this question and highlighted other relationships that might deserve special care? Are the financial backers and scientists working on GE manipulation of trees paying heed to such warnings?

Weediness

The question of whether GE plants—or their relatives—will exhibit enhanced invasiveness has received considerable attention. However, the studies to date have been quite restricted. We suggest that a variety of factors warrant reconsideration of the 'weediness' issue.

First, most scientists think that introducing herbicide tolerance *per se* is not likely to exacerbate plants' invasive potential. However, empirical research on *each* 'line' of GE trees is needed to test this theory (Royal Society 2001, CEQ/OSTP 2001). The recently detected spread of herbicide-resistant canola also raises questions that deserve exploration (Royal Society 2001).

Second, nearly all the studies of weediness to date have been done in managed ecosystems. Regulators also rely on the weed science literature—which rarely discusses whole categories of plants demonstrated to be invasive in natural systems. Among these overlooked natural area weeds are many forestry, horticultural, and pasture plants. [For lists of plants considered invasive in natural systems in the United States, contact the lead author or consult web sites maintained by the Plant Conservation Alliance (http://www.nps.gov/plants/alien) or The Nature Conservancy (http://tncweeds.ucdavis.edu)]. Genetic changes that increase their resistance to herbicides now used to control them would exacerbate problems arising from their invasiveness.

Furthermore, managers of natural systems face pressures that circumscribe their options for controlling invasive plants. The public often demands that they avoid using certain chemicals or biological control. They must minimize damage to non-target vegetation. Finally, they cannot pass on the costs of control. Plants that pose minimal problem in managed systems can become difficult-to-manage, damaging invaders in natural systems.

Third, many scientists believe that a more invasive or weedy plant might result if an introduced gene conveys some increased "fitness"—that is, make the plant more resistant to one or more environmental stresses (Mellon 1993; Louda 1999; Marvier and Kareiva 1999; Royal Society 2001; all wrote about herbaceous plants)—or enables it to grow faster (CEQ/OSTP 2001). Again, proponents and regulators must take greater care to ensure that they are not increasing the fitness of any plant that is already invasive in natural systems.

Finally, genetically engineered trees pose special challenges because plants that have undergone a shorter period of breeding by people are more likely to retain characteristics that would allow them to be 'weedy' than are such crops as maize (Mellon 1993; Royal Society 2001). (Again, horticultural plants and range or pasture grasses have similar short breeding histories).

Evaluating whether a genetically engineered plant might become invasive will not be an easy task. Studies have shown that weediness can manifest as late as 150 years after introduction (Marvier and Kareiva 1999).

Environmental Costs of Managing GE Trees

Techniques adopted to manage genetically engineered trees—including induced sterility and increased use of herbicides—might have their own negative environmental impacts.

Regarding herbicides, the focus has tended to be on 'herbicide ready' trees. If regulators and concerned citizens are to understand the relative risk posed by use of herbicides in plantations of 'herbicide ready' trees, we need better information on the extent to which herbicides are now used in plantation forestry and dependable projections of likely practices using the GE organisms. Society then needs to consider whether there are better ways to solve the weed problem in plantations.

We note, however, that herbicides are expected to be important tools for preventing escape of trees containing a variety of engineered traits. As should be clear from our earlier statements, we concur that it is vitally important to prevent genetic leaks. However, the environmental costs of the management technique need to be evaluated in determining whether to move forward with this technology.

No information is currently available as to whether trees with an altered lignin profile will react differently to pest attack and other stresses. Studies with tobacco genetically engineered for reduced lignin content found the plants to have weaker resistance to viral attack (Maury et al. 1999).

ARE GE PLANTS 'DIFFERENT'?

To a great extent, conflict over the extent of risks posed by genetically engineered trees stems from opposing answers to the question of whether genetically engineered organisms differ in substantial ways from their traditionally bred counterparts.

In presenting the Ecological Society of America's May 2001 statement on genetic engineering, Diana Wall, Director of the Natural Resource Ecology Laboratory at Colorado State University, said "It's important to recognize that some GMOs can possess genuinely new characteristics that may require much greater scrutiny in terms of scientific research than organisms produced by traditional techniques of plant and animal breeding. In particular, we really need more peer-reviewed research on the potential environmental effects of GMOs." The ESA's concern focused on organisms that can persist without human intervention and the exchange of genetic material between GMOs and unaltered organisms within the environment. Some GMOs may also be given traits which would provide an advantage over native species in some environments (http://esa.sdsc.edu/statement0601.htm).

The Royal Society (2001) emphasized that the question of whether GE techniques are no different in character or consequences than traditional techniques must be decided by empirical investigation. The Canadian panel stressed that the assumption that shuffling a crop plant's genome—as happens in traditional breeding—is not likely to create harmful progeny is no longer valid with GE plants, when the novel genes are derived almost exclusively from non-plant sources. The risks are particularly great when dealing with plants that have not undergone millennia of selection to enhance desirable traits and expunge undesirable properties. These plants are more likely to retain a capacity to compete successfully outside of a managed agroecosystem.

The committee that prepared the study by the U.S. Council on Environmental Quality and Office of Science and Technology Policy (2001) was apparently divided on the question. Three of four statements in the report lean toward recognizing substantial differences between conventionally bred and genetically engineered organisms that at least warrant careful study. The first statement notes that, while cross-breeding of organisms has occurred for more than 10,000 years, rDNA technology "vastly expands the potential to introduce new genetic material, [requiring] scientists, regulators, and the public to rethink the adequacy of these existing oversight mechanisms." Later, the report says that the fact that a greater variety of genetic constructs can now be incorporated more quickly into organisms with different genetic backgrounds requires regulatory agencies to develop specific regulations and guidance on their use. Finally, when discussing poplars specifically, the report states, "changes possible by genetic engineering can be different in kind and degree. . . ." On the other hand, the study cites the National Academy of Sciences as twice finding that there is no evidence of unique hazards in using rDNA techniques or in moving genes between unrelated organisms.

The panel of the Royal Society of Canada (2001) justifies its insistence on empirical testing of the similarities and differences between traditionally bred and engineered organisms on the potential risks from pleiotropic effects. According to the panel, when a plant is genetically engineered, the result is not the precise placement of a new piece of genetic code into a carefully selected section of the new host's genome. Rather, each insertion occurs at a nearly random location—resulting in potential differences in the way the gene functions. Furthermore, the remainder of the host's genome is also affected. Insertion of a single gene will be accompanied by a range of changes that will, in turn, be affected by the genome of the host, the host plant's developmental and physiological status, and environmental pressures. Consequently, regulators cannot limit their evaluation of a transgenic variety's potential impacts to those that might arise from the predicted phenotypic characteristics conferred by the transgene chosen for insertion. Instead, officials must empirically assess each genetic line for the potential consequences of these pleiotropic effects. Again, the risk of unanticipated and unwanted changes is greater in plant types with a short history of domestication.

We find interesting the analogies some—including the U.S. National Academy of Sciences—draw between genetically engineered organisms and invasive exotic species. Over the past decade, scientists and the U.S. government have increasingly recognized that efforts to protect the environment from damage by exotic species are inadequate. APHIS regulates genetically engineered organisms under the same legal authority as it manages exotic "plant pests". To the extent that agency's programs have been found to be deficient as regards exotic species (National Plant Board 1999; Campbell 2000), these same programs must also be re-evaluated as they are applied to genetically engineered organisms. Both types of organisms can behave in unexpected ways and cause serious ecological impacts; and these impacts will be hard to predict from data collected in conventional ecological experiments conducted at restricted spatial and temporal scales (Royal Society 2001).

TYPES OF RESEARCH NEEDED AS A BASIS FOR ANALYZING RISK

Among others, the Royal Society of Canada (2001) and Raffa et al. (1997) have outlined research programs that would better support analysis of the potential risks associated with genetic engineering. They agree on the need for broad ecological research conducted by independent scientists. The Royal Society specifically stated that independent ecological research that looks at the potential impacts of GE organisms is more likely to provide novel insights than is research constrained by the regulatory framework.

The Royal Society panel stressed that studies must be of sufficient duration to incorporate the complete lifetime of the GE organism. It recommended a staged approach, involving a series of experimental comparisons with conventional varieties, conducted under ever more realistic conditions. The goal would be to determine whether the GE crop differs from its conventional counterpart in any life-history attribute likely to have fitness implications for survival in the wild. Among the specific studies called for were evaluation of empirical data on the fitness costs and benefits of inserted GE traits in non-crop species taken from diverse ecological contexts; experiments to determine the likelihood of pollen-mediated gene flow to related species; and rigorous experimentation testing the impact of GM plants on both target and non-target insect species. Because of pleiotropic effects, these studies cannot be limited to evaluation of the predicted phenotypic characteristics; they must also assess empirically the unanticipated changes' consequences across time and environments.

The Royal Society panel's report contained many warnings about biases in results that might arise from small scale, short-term studies. The poplar experts convened by the USDA (Strauss 1999) also said that field trials of trees are less likely to provide reliable data because costs dictate that the tests will be too small and too brief to allow assessment of both commercial viability and ecological impacts.

Raffa et al. (1997) suggested ranking risks according to whether they would be localized within the plantation or might affect adjacent ecosystems; whether the environmental harm would be self-perpetuating; and whether potential mitigating tactics are available. They called for proactive research on the likelihood of various environmental hazards (identified in the article) as well as methods for offsetting them. They recommended using an interdisciplinary approach throughout the discovery and development process. We would add that social scientists, economists, and people concerned about social implications, worker health, economic viability should also be consulted.

As stated at the onset, we believe corporations and research consortia involved in developing GE trees should be major contributors to effort to improve scientific knowledge for management of these organisms. This is probably best done by establishing a separate, independent foundation through which could fund independent scientists' work. The current program managed by the USDA Cooperative State Research, Education, and Extension Service (CSREES) is not adequate. Funding is too low—just $1.3–$1.5 million per year. Furthermore, the research is tied too closely to both regulatory agencies and immediate regulatory concerns to provide the longer-term perspective and interdisciplinary approach needed. It is essential that whatever mechanism is established be seen as independent.

Of course, regulatory agencies continue to need scientific assistance in conducting their work. We concur with the Royal Society that the agencies need to be more transparent, to involve a wider variety of expertise, and to reduce the apparent conflicts of interest. Canadian panel proposed many specific actions that we believe could be applied here. In particular, we endorse the panel's call for relying on empirical data, establishing a mechanism to obtain input from independent scientists throughout the regulatory process, and increasing public access to the scientific data and assumptions used in reaching decisions (Royal Society 2001). Finally, we urge expanding the agencies' regulatory authority to ensure that all types of GE organisms are subject to scrutiny and regulation.

THE PRECAUTIONARY APPROACH

There is the potential that at least some of the plausible damaging impacts of genetic engineering might be irreversible, irremediable, and of catastrophic proportions. All parties are currently operating without sufficient scientific data to characterize these risks (Figure 1). Regulators should not assume that the present "absence of evidence" equals an "evidence of absence" of risk. The Canadian panel urged

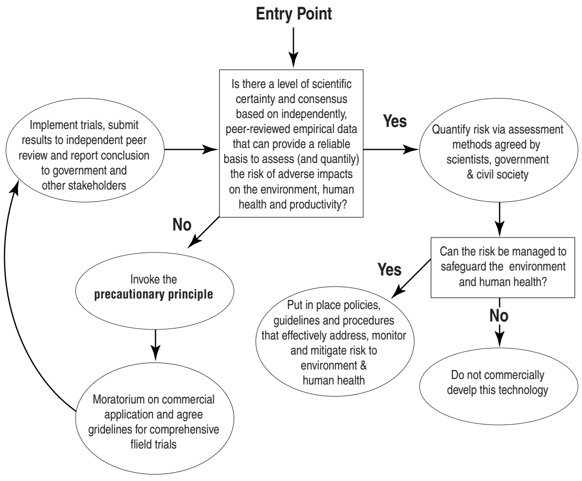

Figure 1. The precautionary principle.

regulators to delay commercial use of any GE organism until the specific genetically engineered line had been thoroughly studied at six relevant levels: genome, transcript, protein, metabolite, health impacts, and environmental impacts (Royal Society 2001).

We endorse the Royal Society's (2001) call to invoke the Precautionary Principle in those cases in which there are some scientific data (although incomplete, contested, or preliminary) or plausible scientific hypotheses or models (even though contested) that establish a reasonable prima facie case for the possibility of serious harm, and there is significant uncertainty.

CONCLUSIONS

The United States lacks a coherent, independent regulatory program for GE organisms that is based on the findings of empirical study. Neither the research establishment nor the regulatory agencies has an adequate process for obtaining the data needed for improving our understanding of the processes, risks, and management options for GE organisms. Controversy about use of this technology will only grow as long as these fundamental flaws not addressed.

To correct these gaps and restore confidence in the U.S. environmental protection regulatory structures, we recommend adoption of the Precautionary Principle for management of genetically engineered organisms. We recognize that the regulatory program is already "precautionary" in the sense that it is intended to prevent or avoid the potential dangers that might arise from GE organisms. Further, scientists have undertaken specific challenges, including efforts to develop sterile organisms, in order to avert possible risks. However, these programs are not as effective as they need to be—largely because of how regulators and proponents of the technology respond to data gaps and uncertainties.

We therefore ask that scientists, institutions, corporations, and regulators adopt a broader conception of the Precautionary Principle—the characterization discussed in the report. The Precautionary Principle is not a license to block a decision; as illustrated here and discussed in the report by the Royal Society of Canada, it is a risk-management strategy for use when the paucity of information precludes quantifying the risks (Asante-Owusu 2001). It shifts the burden to the proponents, in ways which we hope will result in greatly increased funding for independent research into the potential risks and possible management approaches.

We close by reiterating our belief that there are probably alternative, less risky, ways to 'solve' some of the problems GE trees are intended to address. We urge more funding for research into them, as well.

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Biodiversity Implications of Transgenic Plantations

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ABSTRACT

Implications of transgenic plantations on biodiversity vary dramatically depending on context, such as whether the transgenic plantation is replacing an existing tree plantation, a native forest, an agricultural field, or native non-forested vegetation. When transgenic plantations are established in areas not previously occupied by a tree plantation, implications of 'plantation effects' often will be more profound than influences specifically related to the transgenic nature of the trees. Potential 'special transgenic effects' also vary substantially depending on the specific transgenic trait under consideration, and most traits have potential positive and negative implications to biodiversity in an area. Direct off-site effects of transgenic plantations include influences on biotic interactions and landscape structure, and potential escape of transgenic organisms or genes to non-transgenic populations. Indirect off-site effects are primarily related to potential land-use changes stemming from use of transgenic plantations. Although likely indirect off-site effects are generally hypothesized to be positive (decreased pressure for wood fiber production on native forest lands resulting in increased area in reserves), I argue that there are a number of equally likely scenarios that suggest indirect off-site effects would have negative implications for conservation of biodiversity. I discuss a number of lessons from traditional forest conservation issues that may be applied to the debate surrounding transgenic plantations and propose five hypotheses concerning the implications of transgenic plantations to biodiversity.

Use of genetically modified organisms is controversial. Transgenic trees present a complex set of potential societal advantages, ethical issues, and hypothesized environmental risks (Mullin and Bertrand 1998; Matthews and Campbell 2000). Some of the controversy surrounding transgenic plantations concern potential implications to conservation of biodiversity. In this paper, I present an overview of potential biodiversity implications of transgenic plantations. I discuss the likely effects of use of transgenics on biodiversity at different spatial scales, present some pertinent lessons from more traditional forest conservation issues, and propose five general hypotheses concerning the influences of transgenic plantations on biodiversity. Some of the conservation issues related to transgenic plantations are unique to transgenics, others are relevant to intensively managed plantations in general. The potential conservation implications of use of transgenic trees extend beyond transgenic plantations. For example, transgenic disease resistence may facilitate restoration of rare species, such as the American chestnut (*Castanea dentata*). However, this paper focuses solely on transgenic plantations.

SPATIAL SCALE AND BIODIVERSITY

Ecological processes and response of organisms to habitat and environmental condition differ with spatial scale. Similarly, the implications of transgenic plantations to biodiversity also differ with spatial scale. For the purposes of this discussion, I discuss potential effects of transgenic plantations at two spatial scales, local and off-site. Local effects are here defined as influences of transgenic plantations on biodiversity that act at the scale of the forest stand or individual tree. Off-site effects are influences realized at the scale of the landscape or greater. Although presented here as a dichotomy, many of the potential implications actually span multiple spatial scales and it is not always possible to clearly distinguish between local and off-site effects.

Local Effects

Establishment of a transgenic plantation can alter ecological characteristics of an area and potential management practices of a site. Vegetative composition and structure, use of insecticides or other chemicals, and several characteristics of the trees themselves, including resistance to insects, fungi, or bacteria, lignin content of the wood, and flowering and fruiting can all be altered through establishment of a transgenic plantation (Matthews and Campbell 2000). At the local scale, the implications of establishing a transgenic plantation to the biodiversity of an area vary substantially with the context in which the plantation occurs. For example, the biodiversity implications of converting an existing non-transgenic hybrid poplar plantation to a plantation of transgenic poplars is very different from the implications of converting a native forest to a transgenic poplar plantation. Biodiversity implications of conversion of an existing plantation to a transgenic plantation of the same species are restricted to 'special transgenic effects', whereas conversion of some other type of vegetative community to a transgenic plantation include influences related to special transgenic effects and 'plantation effects'.

Special transgenic effects

Special transgenic effects are the unique influences of transgenic organisms that manifest because of consequences related to expression of the transgenic trait. Special transgenic effects vary greatly depending on the specific transgenic trait. Most transgenic traits can have positive or negative influences on local biodiversity (Table 1).

For example, transgenic plantations of trees with insect resistance would certainly impact abundance, species richness, and diversity of insects in transgenic plantations. Indeed, reduction of certain populations of insects is the very outcome desired by use of transgenic, insect-resistant trees. Reductions in insect populations could have cascading ecological effects through the food web. Birds, bats, shrews, spiders, and other animals that rely on insects for forage could be affected by changes in the forage base. However, while use of insect-resistant trees would certainly have implications to the biodiversity of the stand, the net impact of use of transgenics in this case is not necessarily negative. Use of insect-resistant trees would likely result in reduced use of insecticides in the plantation. Reduced insecticide use could result in decreased impacts on non-target species, such as those feeding on ground vegetation.

Actual or functional sterility is often considered to be a desirable trait in transgenic plants, as this would eliminate or greatly reduce potential of flow of transgenic genes (via pollen) or propagules (via seed) outside of the plantation (Strauss et al. 1995) (although sterility may not eliminate movement of transgenic material in species with active vegetative reproduction). Reduced flow of transgenes or propagules presumably has positive implications for biodiversity. However, in cases where other species depend on the pollen, nectar, seeds, or fruit of plantation trees, sterility could result in cascading ecological effects, whereby the species dependent on the flowers or fruit would be negatively impacted. Clearly these effects are dependent on the tree species of interest and the com-

Table 1. Some potential influences of special transgenic effects on biodiversity at the local scale.

Transgenic trait	Positive effect	Negative effect
Insect tolerance	Reduced use of insecticides	Impacts on trophic relationships
Fungal resistance	Reduced use of fungicides	Impacts on trophic relationships
Reduced lignin content	?	Impacts on decay organisms
Plant sterility	Reduced gene transfer	Impacts on trophic relationships

munity of organisms present in the plantation and surrounding area.

Likely biodiversity effects of some transgenic modifications, such as alteration of lignin content of trees, are unclear. There are potential implications of altered lignin content for decomposers or for species that forage on organisms that live in the wood, but I suspect that these implications are likely to be relatively small.

Plantation effects

Plantation effects are the consequences of the vegetative species composition and stand structure in a tree plantation. As organisms generally respond strongly to vegetative composition, stand structure, and aspects of the physical environment mediated by vegetative communities, plantation effects can have a profound influence on the biodiversity of an area. Indeed, when transgenic plantations are planted in sites not previously occupied by a plantation of the same species, implications of plantation effects are likely to greatly outweigh implications of special transgenic effects at the local scale. Just as the influences of special transgenic effects vary among transgenic traits, plantation effects vary with the type of vegetative community present prior to establishment of the transgenic plantation (Figure 1). In general, biodiversity implications will be negative when native forests are converted to plantations. Relative to native forests, transgenic plantations are generally structurally simple, have minimal vegetative species diversity, and lack many of the specialized habitats that are relied upon by a diversity of species. Similarly, conversion of other native vegetative communities, such as native grasslands or savannah, to transgenic plantations generally would result in negative implications to biodiversity. Frequently, areas that could be converted to transgenic plantations do not currently support native vegetation. Local consequences of conversion of these lands, such as agricultural fields, to biodiversity in transgenic plantations could have negative, neutral, or positive effects, depending on the characteristics and management of the transgenic plantation and the agricultural field.

Direct Off-site Effects

The influences of transgenic plantations often may extend beyond the immediate plantation and influence biodiversity in surrounding areas. Direct off-site effects are the influences of the presence of transgenic plantations on biodiversity of areas outside of the plantation. Three potentially important implications are: introduction of propagules and transfer of genetic material to other sites, influences on biotic interactions, and influences on landscape structure.

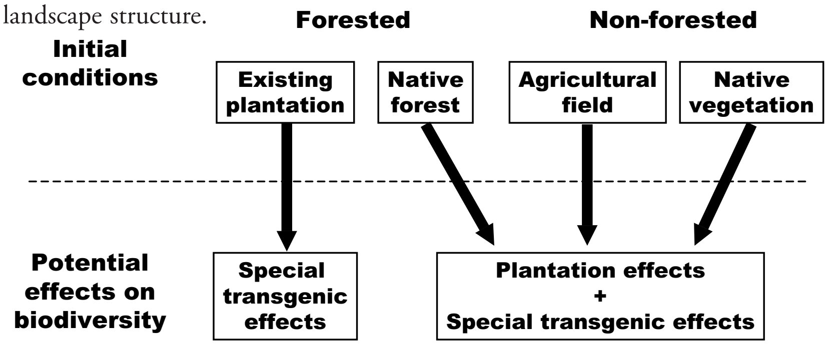

Figure 1. The influences of transgenic plantations on biodiversity at the local scale depends on context.

Movement of propagules and transfer of genetic material

There has been considerable attention to issues related to escape of transgenic plants to other environments and introgression of transgenic genes to non-transgenic plants. Although often considered together, these two issues actually have very different potential implications to biodiversity and the contexts in which they are important also differ.

Transfer of transgenes can only result in significant biodiversity implications where there are native or introduced non-transgenic species that are genetically similar enough to the transgenic species to allow introgression and that are geographically close enough to allow the transfer of genetic material. Probability of spread is influenced by the phenotypic expression and selective advantage imparted by the trait (James et al. 1998). Introgression of transgenes presents reduced risk when transgenic plantations are composed of exotic species with no genetically similar species nearby. In addition, use of sterile transgenic plants would also eliminate or greatly reduce potential for transgenic introgression. When introgression of transgenes from a transgenic plantation is possible, it could have implications to biodiversity if one of two conditions are met. First, if the special transgenic effects of the trait pose significant implications to biodiversity, introgression could be an important issue. Conversely, if the special transgenic effects of the transgene do not have significant implications to biodiversity, then its introgression is of lesser importance. Second, even if the transgenic trait has no evident direct implications to biodiversity, introgression could be important if it influences genetic diversity within the species in some important way.

Movements of propagules of transgenics out of transgenic plantations can also be reduced through use of sterile transgenic plants, but even when using sterile plants escape of some transgenics is possible for species with vegetative reproduction. It is possible, but highly unlikely, that many of the transgenic traits under consideration today would increase the probability of escape of propagules (Hancock and Hokanson 2001). In contrast to issues related to introgression, escape of exotic species (transgenic or otherwise) generally pose greater potential impacts to biodiversity than would escape of transgenic native species, especially if the transgenic plants are sterile.

Influences on biotic interactions

Just as special transgenic effects could influence biotic interactions, especially trophic relationships, at the local scale, transgenic plantations could also influence biotic interactions at larger spatial scales. Influences are potentially greatest for trophic relationships of wide-ranging species, such as birds and bats. Locally induced changes in species composition within a plantation could influence competitive relationships or food webs at larger spatial scales.

Influences on landscape structure

Intensively managed plantations can influence the composition and configurations of landscapes. Transgenic plantations can play a role in increasing or decreasing fragmentation and connectivity in an area. The influence of a transgenic plantation on landscape structure, and the resulting implications to biodiversity, are highly context dependent.

Indirect Off-site Effects

Use of transgenics may have a number of indirect, but highly significant, effects on biodiversity. Indirect off-site effects are the consequences of changes in land use precipitated by use of transgenic plantations. One possible indirect effect, often cited by proponents of use of transgenic plantations, is that high-yield transgenic plantations will decrease the pressure for wood fiber production on other forest lands. The potential for this outcome is well documented through modeling (Sedjo 2001; Victor and Ausubel 2001). It is often further postulated that, as a consequence of this, a larger proportion of forested lands would be available for biodiversity reserves. However, increased area in biodiversity reserves is only one potential outcome of widespread use of transgenic plantations, and I contend that it is not necessarily the most likely outcome. I argue that the assumption that decreased pressure on native forests for production of wood fiber equates to positive benefits for biodiversity is naive. Just as implementation of intensive agriculture and increased productivity of agricultural lands did not result in large areas devoted to conservation of native grasslands in the United States, increased productivity of tree plantations would not necessarily result in increased area allocated for conservation of native forests. Although establishment of biodiversity reserves for some of the lands under public ownership is conceivable under this scenario (although even this is highly dependent on the social, political, and economic environment in which the public lands occur), it seems highly unlikely that native forest lands that are currently under private ownership would be allocated to biodiversity reserves if pressure for wood fiber production on those lands decreased. On private lands, sustainable management of native forests for both commodity and non-commodity values may be the key to conservation of biodiversity. Highly productive transgenic plantations could decrease the economic value or perceived social value of maintaining native forests in a forested condition. This could result in increased conversion of native forests to transgenic plantations or conversion of native forests to non-forest use, such as agriculture or housing. Conversion of native forests to plantations or a non-forested condition would generally have negative implications for conservation of biodiversity.

High economic value of transgenic plantations also could spawn conversion of lands under some other form of land use to transgenic tree plantations. If transgenic traits are developed that enable establishment of plantations in areas that currently have unsuitable growing conditions, resulting changes in land-use patterns have potential biodiversity implications. As with local effects, the exact nature of these implications are dependent on context, and could be either positive or negative.

Indirect off-site effects of use of transgenic plantations are likely to be highly significant. Actual implications could either be negative or positive depending on the way that lands freed from pressures of production of wood fiber are managed. Future patterns of land use are somewhat unpredictable and unraveling the interactions among economic patterns, population growth, consumption, and patterns of land use is complex. However, more realistic assessment of likely implications of increased productivity of transgenic plantations could be modeled under a range of social, political, and economic assumptions.

SOME LESSONS FROM TRADITIONAL FOREST CONSERVATION ISSUES

Our understanding of the implications of transgenic plantations on biodiversity remains in its infancy. Many of the questions concerning the potential biodiversity implications of transgenic plantations to biodiversity are yet to be fully developed. Many of the potential biodiversity issues raised to date may prove to be unimportant, and other issues that currently have yet to be hypothesized may emerge. Although some of the issues related to biodiversity and transgenics could be unique, many of the issues parallel more traditional issues in conservation of biodiversity typical of other forest systems. Consequently, many of the issues concerning conservation of biodiversity in more traditionally managed forests are likely to have relevance to transgenic plantations. Here I present four lessons relevant to transgenic plantations based on my personal experiences working with forest conservation issues.

Separating scientific issues from social and ethical issues is critical.

In recent years, conservation of biodiversity has become a powerful issue influencing land management decisions, and scientific knowledge of biodiversity implications has become an important metric for evaluation of management approaches. As a result, arguments that are not scientific in nature or that only tangentially pertain to biodiversity are sometimes presented under the guise of science and conservation of biodiversity. In some cases this results from an honest misunderstanding of the science underlying an issue. In other cases, public opinion and social and ethical issues are dressed up in the lexicon of science to enhance their apparent credibility. Perhaps this is a reflection of an unfortunate under-valuation of ethical issues and public opinion relative to scientific understanding in the decision-making process. Regardless of the reason, confusing ethical and scientific implications often muddles the debate and the decision-making process. Informed decision-making and meaningful debate best results when social preferences and ethical implications are given strong weight, and when scientific issues are clearly separated from non-scientific issues.

Biodiversity may be conceptually too broad to provide criteria for decision-making.

Attempting to manage for biodiversity is a noble goal, but is nearly impossible to implement as a management objective. Because the concept of biodiversity is so all-encompassing, managing for biodiversity is probably too broad a concept to provide a meaningful metric for decision-making and for evaluation of management alternatives. Persistence or viability of key species or guilds of interest, maintenance of specific ecological functions, and maintenance of genetic resources in an area are examples of characteristics that, although sometimes difficult to measure, are generally more tractable than broad goals related to biodiversity. Refinement of the biodiversity objectives for areas considered for establishment of transgenic plantations is a necessary step to evaluation of the conservation implications of a management scenario.

All resources and values can not be maximized on every parcel of land.

It is not possible to maximize output of all resources and forest values on every parcel of land. Clear identification of the goods and services desired from lands under a given land allocation is a necessary step to evaluation of the societal acceptability of different management alternatives. What ecological goods and services are desired from lands managed intensively for wood fiber production? How important is conservation of biodiversity on these lands? Are the societal goals the same for transgenic plantations that occupy 20 hectares as for plantations that occupy 1000 hectares? Although scientists can help elucidate the implications of establishment of transgenic plantations on different aspects of biodiversity, these questions are inherently non-scientific in nature. If there is minimal expectation for transgenic plantations to play an important role in conservation of biodiversity at the local scale, then the focus shifts to the likelihood and magnitude of off-site effects. The answers to these questions may differ among individuals and societies. In any case, more clear resolution of these questions would be highly valuable to help focus the issues of concern.

A strong information base is essential to facilitate intelligent decisions.

Land management and environmental issues often are inherently controversial and subject to strong emotion on all sides of an issue. A strong scientific foundation is necessary to evaluate the ecological implications of management activities. Such a foundation is entirely lacking for issues related to biodiversity and transgenic plantations. In the absence of such data, arguments and debates concerning the influences of transgenic plantations on biodiversity are based on speculation and logical argument, and are often shaped by personal values and beliefs. Some questions and issues can be addressed through modeling studies and small-scale experiments, but many important questions can only be answered from field-based, stand-scale studies.

Furthermore, some questions concerning the implications of special transgenic effects can only be answered in transgenic plantations. However, substantial progress on many relevant ecological questions can be made through studies in existing non-transgenic plantations. Ecological research in non-transgenic plantations could answer a subset of the questions and help refine research questions to be asked in transgenic plantations.

ARE THERE ANY GENERAL PRINCIPLES?

There are numerous uncertainties concerning the biodiversity implications of transgenic plantations. The uncertainties are further exacerbated by the fact that the implications are highly dependent on context. Implications are likely to differ with transgenic trait, species of tree, size of plantation, management approach, landscape context, and geographic area. Are there any general principles? In the absence of empirical data, the answer to this question is debatable. Here I propose five hypotheses concerning likely implications of transgenic plantations to biodiversity. I present these hypotheses to stimulate debate and research, rather than as a set of incontrovertible principles, although with evaluation these hypotheses may form the basis for a set of general principles. These hypotheses also could provide the foundation for a program of research to investigate the influences of transgenic plantations on biodiversity.

Hypothesis 1: Biodiversity implications will be greatest when transgenic plantations replace or impact the amount of native forest.

This hypothesis is likely to be equally true for transgenic and non-transgenic plantations, but because of the potential for substantial increases in productivity and economic efficiency in transgenic plantations, the potential of transgenic plantations to influence the amount of native forest may be greater than for non-transgenic plantations. As noted above, transgenic plantations have the potential to relieve some of the pressure on native forests to produce wood fiber, and this could either increase area of biodiversity reserves or increase conversion of native forests to non-forested land. The extent to which use of transgenic plantations influences area of native forest could have great implications to conservation of biodiversity.

Hypothesis 2: Biodiversity implications of special transgenic effects will be greatest when traits are have cascading ecological effects manifested at multiple spatial scales.

Use of transgenics may alter food webs, and thus transgenic plantations could have cascading ecological effects on biodiversity. Alteration of foliage characteristics and production of flowers, fruit, and seeds could have implications that resonate throughout the food chain. Effects that are exhibited at multiple spatial scales and influence trophic relationships outside the plantation are likely to be the most significant.

Hypothesis 3: Genetic implications to biodiversity are greatest when transgenic plants are established near enough to genetically similar species to allow introgression.

Issues related to introgression can be eliminated or greatly reduced through use of sterile organisms. In cases where fertile or partially sterile plants are used, use of exotics with no genetically similar species nearby would further minimize potential consequences of introgression of transgenes.

Hypothesis 4: Ecological implications to biodiversity are greatest when exotic species are used in transgenic plantations.

Although genetic implications are generally reduced through use of exotics, ecological implications of using exotic transgenics are greater than for use of native transgenics. Ecological consequences of escape will generally be greater for exotics than for native species. In addition, plantations of native species are more likely to provide similar ecological niches as found in native forests.

Hypothesis 5: Biodiversity implications of transgenic plantations are a function of structural complexity of the plantation.

The number and types of ecological niches available for species often is a function of the structural complexity of an area. As a result, structurally complex environments are generally more species rich than are structurally simple environments. Forest plantations are often structurally simple, although the complexity of plantations can vary dramatically with species and management approach. Depending on how employed, use of transgenics could result in an increase or decrease in structural complexity of plantations. For example, transgenic herbicide resistance would likely alter patterns of herbicide use in plantations. Altered use of herbicides in a manner that increases amount of understory vegetation would likely have positive effects on biodiversity, whereas decreased understory vegetation would likely have negative effects on biodiversity. Creative use of transgenics in plantations could increase the structural complexity of the plantation, if this were a goal of plantation managers.

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Potential Impacts of Genetically Modified Trees on Biodiversity of Forestry Plantations: a Global Perspective

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ABSTRACT

Contrary to popular belief, plantations can harbor a significant part of woodland natural biodiversity, and some plantations are crucial to the survival of certain specialized birds and mammals, especially in areas where plantations are managed specifically to enhance wildlife. There may be compelling environmental reasons for increasing plantation areas in the future, including introducing GM plantations, if adequate biosafety can be achieved. If these new GM plantations replace farmland or low-density plantations, this could alleviate commercial pressure on old-growth forest, with considerable benefits to global biodiversity.

Improvements to forest trees via conventional selective breeding are severely limited, but transgenic technology offers the opportunity to domesticate trees, to tailor their characteristics more closely to the requirements of commercial forestry and the end-user of forest products. Transgenic techniques can produce varieties that enable different management regimes to be used to grow them. This is especially important in agricultural crops and trees, where the use of agrochemicals can be changed by transgenic traits such as herbicide tolerance, and pest and disease resistance. Such changes can have both adverse and beneficial impacts on native biodiversity in contact with agriculture and forestry. The impact of GM varieties on biodiversity is much more likely to depend on the traits they possess, and not the process by which such traits are achieved.

The potential impact on biodiversity of transgenic herbicide tolerant forest trees lies in their ability to be able to withstand the application of broad spectrum herbicides used to control competing vegetation especially in the early stages of plantation establishment. The early stages of plantations are known to be important for woodland biodiversity, whether plantations are being newly established on open land, or are replacing felled trees. It might be expected that the effects of herbicides used on GMHT trees would lead to widespread weed kill, which in turn would give improved tree growth and quicker and more complete canopy closure. If herbicide tolerant trees are ever to be used in GM plantations, there would need to be management schemes to counter any adverse effects on natural biodiversity. These could include factors such as leaving areas unsprayed to act as the equivalent of 'rides' and 'glades' in non-GM forests.

Changing the quality of timber in growing trees has long been a goal of plant breeders. Transgenic technology offers a way of achieving radical changes in factors such as the lignin-to-cellulose ratio of both conifers and deciduous hardwoods. In doing so, there is the potential to alter the palatability of such trees to phytophagous animals, with consequent damage to the trees. This could lead to the need for more agrochemical management of such plantations, or for the insertion of multiple traits such as insect, fungal, and viral resistance to combat such damage.

Concerns about gene transfer to and from transgenic trees has led to increased research into mechanisms for engineering sexual incompetence into transgenic trees. The

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result is likely to be trees that produce little pollen, and few flowers, seeds, and fruits. Not only are these food resources important for supporting biodiversity in coniferous and deciduous hardwood forests, they are also important economically in some parts of the world, especially where plantations produce copious nectar that can support bee-keeping enterprises. If sexual incompetence is necessary for biosafety reasons, then single variety plantations may be undesirable, and mixed varieties (GM and/or conventional) stands would be preferable. There may also be biosafety advantages in growing mixed stands of GM and conventional trees, specially in reducing selection pressures for the evolution of pest resistance. Mixed stands could also be designed to further reduce gene flow in situations where sexual incompetence mechanisms in GM trees are not totally effective.

In assessing risks from annual GM crops, it is possible to carry out comparative ecological studies, such as the farm-scale evaluations of GMHT crops in the UK. With long-lived perennials such as trees, however, a predictive modeling approach is the only realistic option if regulatory authorities are to make decisions on consent for release within a reasonable time scale.

Debate about the use of biotechnology to create transgenic plants and animals has largely centered on the perceived direct risks and benefits of introducing new genes into crops, fish, and trees. Concerns about food safety and gene transfer have dominated the debate, but there has been relatively little discussion about how plants and animals possessing transgenic traits might enable new forms of agriculture, aquaculture, and forestry management with consequent indirect risks and benefits. Historically the impacts of new management regimes in agriculture, fish farming, and forestry have been profound, changing whole landscapes and their associated biodiversity. This paper focuses on assessing the possible effects of genetically modified (GM) trees on the biodiversity of forest plantations, and does not address in detail how the use of transgenic trees might impact on forestry strategy, such as the possibility of high-yielding GM forests replacing old-growth cropping as a prime source of high-quality timber, pulpwood and other forest products.

Plantations have been a major part of European forestry for at least 300 years, and are an increasingly important feature of commercial forestry throughout the globe. Research has revealed much about how plantation composition and management affects the ecology of the natural biodiversity found in and around plantations. The ecological principles revealed by this research effort, centered in the conifer plantations of Europe and the pine plantations of the southern United States, are applicable to plantations worldwide.

PLANTATION ECOLOGY

Large-scale afforestation of agricultural and marginal land has been practiced in Europe since the 18th century and in some areas, old-growth forests have been replanted either in part or by complete replacement of the ancient trees. Plantations now make up over 50% of all forests and woodlands in Europe and supply a higher proportion of timber and other forest products than old-growth forests (Peterken 1993). It is estimated that the area of plantations worldwide is over 185 million ha, of which around 60% are in temperate regions and around 40% in the tropics (FAO 2000).

Plantations are not only the most productive and profitable forest areas, but can also make a significant contribution to general biodiversity; in some regions of Europe they harbor most of the forest biodiversity. However in other parts of the world plantations make a relatively minor contribution to forest biodiversity, often replacing highly diverse ecosystems with species-poor monocultures. However, some tropical plantations on low-grade farmland can be ecologically diverse. For example, in Malaysian plantations of *Eucalyptus* moth diversities can be as high as those in natural secondary forest (Chey et al.1997).

In Europe and North America, the planting dates and management history of new and replacement woodlands are sometimes well documented, allowing research to be carried out comparing plantations of different ages and tree species in a large number of different locations with differing management regimes. The biodiversity of American and European plantations has therefore been the subject of much research over the past 40 years, with the results of research being used as a basis for planting schemes and management regimes that favor high biodiversity in plantations that also give high timber-crop yields.

In North America, Asia, and parts of Central and Eastern Europe, plantations on previously afforested areas are increasingly replacing old-growth forests that have been logged, leading to increasing concern about the survival of species associated with ancient forest areas, some of which are still being logged. In order to maintain timber production in these regions, conservationists and foresters have argued that substantial areas of new plantations on open land will be necessary to alleviate commercial pressure on natural forests, especially those still retaining large areas of primary old-growth forest ecosystems (Shepherd 1993).

These arguments are being increasingly applied to tropical areas of Africa, Asia, and the Pacific Rim, where commercial pressure on rain forests and other natural ecosystems is leading to severe degradation of natural biodiversity, climate, water resources, and soils. Plantations of commercially valuable trees such as teak, mahogany, and eucalyptus are increasing in area as logging from natural forests becomes more difficult both physically and politically.

If plantations are to replace a significant proportion of present-day commercial production from old-growth forests, there is a strong argument to make them as productive as possible in terms of both yield and quality, and also to lower management inputs. This ‘intensive silviculture’ (Moore and Allen 1999) is being rapidly adopted throughout the world as a way of increasing production per unit area whilst simultaneously reducing unit production costs. In common with development of transgenic agricultural crops, most research on GM trees has concentrated on traits aimed at securing these goals. Pest and disease resistance, modified quality traits such as altered lignin content, and tolerance to herbicides have been the main traits for transgenic trees, with current research also focusing on domestication of trees through transgenic traits for accelerated breeding (e.g., precocious flowering) and genomics research. There is also increasing research interest in genetically modifying trees to enable them to be grown in saline and arid soils.

There has been little consideration of the effects that plantations of GM trees might have on forest ecology and biodiversity, but generally, in intensively managed landscapes, the establishment of plantations on land that has been previously managed as arable farmland and sown grassland results in a net gain for biodiversity (Nature Conservancy Council 1991), whereas replacement of old-growth forest and semi-natural vegetation by plantations often lowers biodiversity, favoring colonizing, ruderal flora and fauna over the diverse wildlife of natural ecosystems (Nature Conservancy Council 1986), but this is not always the case for all taxa. For example, recent research in the UK reveals that species richness of macrofungi in conifer plantations is as high as that of semi-natural pine and oak woodlands (Humphrey et al. 2000).

The biodiversity of forest plantations depends on a number of factors, of which the following are the most important.

Size

Larger plantations generally support more biodiversity (Peterken 1993). This is mainly because in large forests there are likely to be more sources from which propagules of woodland species can colonize the plantations, and larger forests are more likely to contain a wider variety of geomorphological features than small woodlands. This means that larger plantations are more likely to contain more biological and physical 'niches' that can be exploited by woodland wildlife.

Sources of woodland species already on site or nearby

Peterken and Game (1984), in an extensive review of the biodiversity of plantations in the UK, found that woods that had been planted adjacent to ancient woodland and old woodland/hedge features were much richer in woodland biodiversity, and so were those that included water features such as streams and rivers.

Age of Forest

Studies (e.g., Peterken 1993) comparing vascular plant colonization of plantations of different ages have found that older plantations are slightly richer than recently planted stands, but after around a century of establishment, plantations do not gain in vascular plant richness, presumably because as new species colonize, early colonizers die out. Although rates of colonization of specialist woodland plants are often very slow, especially into closed-canopy mature stands, some insects, birds, and mammals rapidly colonize new stands, taking advantage of the physical and biological resources provided by the trees themselves.

Tree Species

Within the temperate zone, insect and bird diversity is generally much higher in deciduous stands, especially those where abundant tree flowers and seeds are available. Deciduous stands usually have a greater diversity of physical structure than conifers, especially if the latter are even-aged single species stands (Moss 1979). Tree species diversity within plantations is also important because stands that have a mixture of tree species can be expected to have a wide range of tree architecture and food resources, not only from the foliage, flowers, and seeds of living trees, but also in the range of saprophytic fungi and other species feeding on deadwood.

Management

Biodiversity is higher in stands that are managed for diverse forest architecture. Small coups areas and short rotations maintain higher natural biodiversity because they result in variable age structure between coups, and more regular opening up of the forest floor, allowing flora and fauna to benefit. Smaller coup areas also provide more forest rides and firebreaks, which are also very important, both as sources of colonization and for the provision of 'forest-edge' habitats, which favor high insect and bird diversity. Studies in the United States and Europe (Mitchell and Kirby 1989) indicate that the more diverse the spatial and temporal physical architecture, the higher the biodiversity of the forest, no matter which tree species are planted.

Generally, high plant abundance and diversity ("forest weeds") in early stages of plantation growth are important for the survival of insects and breeding birds (Moss 1979). The highest natural biodiversity is found where managers practice localized weed control around the growing trees, leaving areas between the crops to undergo natural succession. In many parts of the world, tolerating weeds (including native trees and shrubs) in young plantations could have a severely damaging effect on establishment of the planted trees, especially in some parts of the tropics where colonization by grasses and native woodland shrubs can easily out-compete the crop. This may be less of a problem in temperate regions, where tree growth can overcome competing flora, often with little intervention other than pre-planting weed control. Single-application weed control measures may not have long-lasting effects on non-crop plant and insect diversity, and if forest managers use herbicides carefully, leaving some areas untreated, biodiversity can be maintained (Morrison and Meslow 1984; Santillo et al. 1989; Mellin 1995).

The sporadic use of insecticides in forestry management can have adverse impacts on non-target animals, although these effects are usually confined to short periods after application, with recolonization rapidly replacing the fauna. Stribling and Smith (1987) showed that in oak/maple forests in the United States, spraying insecticides for the control of gypsy moth did not appear to damage bird populations. In contrast, pine beauty moth control programs in Canada had short-term adverse effects on birds (Spray et al 1987).

Nutrient Levels and Geology of Soils

High nutrient levels on clay soils give an impoverished ground flora composed of a few very competitive species, whereas the ground flora of plantations on sands, peat, and loams with lower nutrient levels are generally more diverse (Ferris et al. 2000). Soil types also affect the capacity of plantations to acidify watercourses within them. Peat soils in particular can exacerbate acidification, adversely affecting the ecology of forest streams and the lakes and rivers into which they flow (Stoner et al. 1984). The replacement of deciduous forest by conifers can also significantly reduce stream flow by increasing transpiration and intercepting rainfall, damaging the ecology of woodland streams (Swank and Douglass 1974).

POTENTIAL EFFECTS OF GM TREES ON PLANTATION BIODIVERSITY

Biotechnology is an important extension of conventional breeding techniques, not least because the technology enables radical changes in phenotypes through the insertion of gene cassettes that confer new traits. These changes are often not achievable using conventional breeding techniques, partly because the time taken to find or construct suitable genes would be inordinately long, but mostly because the genes necessary to produce desired traits are not present in the gene pool of the species and its ancestors.

Transgenic techniques, like other forms of plant breeding, produce varieties that exhibit different phenotypes from their ancestral form, which in turn enable different management regimes to be used to grow them. This is especially important in agricultural crops and trees, where the use of agrochemicals can be changed by transgenic traits such as herbicide tolerance, and pest and disease resistance. Such changes can have both adverse and beneficial impacts on native biodiversity in contact with agriculture and forestry (Johnson 2000). Conventional breeding can produce agricultural crops with similar traits (e.g., herbicide tolerance and pest resistance), but selecting for such traits is very difficult to achieve in forestry tree species, where plant breeders have to contend with long generation times and traits that may only manifest themselves at maturity. With the advent of biotechnology and cloning techniques, there is the real possibility of developing domesticated trees that produce timber and other products that are closer to market needs, and of producing trees that can be grown more easily and quickly in plantations.

The impact of such trees on biodiversity is much more likely to depend on the traits they possess, rather than the process by which such traits are achieved. Currently the traits discussed below are more easily achieved using transgenic techniques, but in the near future an increasing knowledge of tree genomics, coupled with marker-assisted breeding, may be capable of producing similar results.

GM Herbicide Tolerance (GMHT)

Table 1 shows that herbicide tolerance is one of the main areas of research and development in transgenic trees. This research effort has been fo-

Table 1. Number of GM tree field trials, 1988–2000.

Genus	HT	IR	VR	Lignin	Markers	Others	Total
Betula				1	1		2
Castanea	1						1
Corcia			10		2		12
Eucalyptus	4		1	2	3	2	12
Juglans		7	1			7	15
Liquidambar	3						3
Malus	5	6			2	16	29
Olea					2	2	4
Picea		3				3	6
Pinus	1	1			11	2	15
Populus	41	36		10	14	42	143
Prunus			3		3	1	7
Pyrus						3	3
Total	55	53	15	13	41	75	252

Note: HT = herbicide tolerance; IR = insect resistance; VR = virus resistance. "Other" traits include fungal resistance, salt tolerance, altered flowering, and faster growth.

Source: Rautner, M., 2001. *Biotech and Development Monitor*. 44/45, pp. 2–7, Amsterdam.

cused on achieving tolerance to broad-spectrum herbicides such as glyphosate and glufosinate-ammonium. These herbicides are commonly used in conventional forestry to control vigorous species of grasses, herbs, and shrubs that compete with the planted crop.

The main effect of using herbicides in forestry plantations, whether conventional or GMHT, is the potential for destruction of native woodland flora and dependent fauna already present on site. Drift to watercourses and hedge banks within and on the margins of plantation sites can result in destruction of flora that are potential colonizers of the developing woodland. Pre-planting destruction of these flora and their associated fauna could result in impoverished forest ecosystems in GMHT plantations in later years. Pre-planting herbicide regimes for GMHT plantations would be similar to those already being used, and can be expected to have similar impacts on native biodiversity. At present, herbicide application after planting often risks damaging conventional trees, especially where competing wild plants require high concentrations of herbicides for effective control. The introduction of herbicide tolerance would allow broad-spectrum weed control at any stage in plantation development, but would be most likely to be used in the early stages of tree growth, when a wide range of forest and forest-edge species tend to be present.

If GM trees tolerant to broad-spectrum herbicides were to be widely used, GMHT plantations could be less attractive for species of birds and invertebrates that rely on young plantation habitat, with its combination of young planted trees and diverse wild plants that support the food webs on which they rely. Santillo et al. (1989) and Morrison and Meslow (1984), for example, found that herbicide treatments of felled and replanted forest significantly reduced the abundance and diversity of phytophagous arthropods. Studies in Sweden have linked the diversity and abundance of insectivorous birds with the availability of herbivorous insect larvae in *Picea* forests (Atlegrim and Sjöberg 1996).

Widespread and routine application of broad-spectrum herbicides to new plantations might prevent the establishment of woodland understory species that rely for germination on the light and moisture of newly planted stands. Woody shrubs generally cannot germinate in closed-canopy forests, and establish themselves either early in the plantation successional stages or only very much later after the stand has been thinned. In the absence of these shrubs, plantations are poorer in wildlife because they are not only simpler in species composition but also in terms of structural diversity.

Tolerance to Adverse Soils

Drought resistance and tolerance to acidic and saline soils are active areas of research into transgenic trees. These characteristics may eventually enable afforestation of areas having soils where commercially valuable trees are currently unable to grow successfully. This could be beneficial to biodiversity and general environmental health if it allowed trees to thrive on agriculturally degraded soils, providing soil stability, soil refurbishment, and carbon sequestration.

However these developments also raise the possibility of plantations growing on soils that do not naturally support a characteristic woodland flora and fauna. Plantations on saline soils may develop a ground flora and understory of species found in shaded gullies in saline habitats, such as salt flats and salt marshes. In the tropics, salt-tolerant plantations might support associated wildlife characteristic of mangrove swamps, especially in coastal and river floodplain locations. However, there may be relatively few plant species capable of tolerating the double stress of shade plus high salt levels.

The implications for biodiversity of these developments are difficult to predict from ecological theory. Only by establishing pilot-scale plantations can ecologists begin to understand the impacts of afforesting saline and arid areas with their established and highly adapted ecosystems.

PEST AND DISEASE RESISTANCE

GM Insect Resistance (GMIR)

It has been argued by some contributors to the GM debate that the introduction of insect resistance into forest trees would render plantations devoid of phytophagous and pollen-feeding insects (Owusu 1999 and Tickell 1999). Whilst this may be a risk where broad-spectrum anti-feedants and insecticides (such as lectins and protease inhibitors) are produced by GM trees, more specific transgenic insecticide resistance such as Bt is only likely to have significant adverse effects on woodland ecosystems where the IR trait impacts on keystone phytophagous species, such as Lepidoptera and Coleoptera, that are themselves endangered or are crucial parts of food webs supporting rare or endangered species of birds or mammals. This could be a greater risk in tropical areas, where rare species may be more specialized in their food and habitat requirements than in temperate zones. The introduction of trees containing Bt toxins in these situations could have a significant adverse effect on these rich ecosystems. Lectins and protease inhibitors may be more generalized in their effects, and risk destroying or deterring most arthropods, and probably mammals and birds feeding on the trees, but exposure to the toxins would depend on levels of gene expression in various parts of the GM trees.

These risks must be assessed in relation to the risks posed by the use of insecticides to control pests in conventional plantation management. Risks from conventional pesticide use are relatively low due to the sporadic nature of insecticide use in conventional forestry, and the capacity of woodland fauna to recolonize after insecticide use. Without comparative research it is difficult to estimate relative risks to biodiversity of introducing GMIR traits into trees. This is compounded by the difficulty of predicting long-term effects, especially where both target and non-target insects could develop resistance to the trait. Current proposals for managing such risks usually assume that resistance in insects would effectively be a recessive trait if high doses of Bt toxin were used in the transgenic plants (Andow et al. 1998). This is a rather speculative assumption that, if incorrect, could prove fatal to resistance management schemes relying on maintaining refugia of susceptible insects (Gould 1998; Andow et al. 1998). If pest populations and non-target insects develop resistance to the GMIR trait, and this is likely where the trait is inserted into long-lived trees, then there could be a long-term management trend towards increased insecticide use. Although target pest populations may be reduced by an IR trait, this could allow other, previously rare, 'secondary' pest species to flourish, leading to increased need for conventional chemical control (Sharma and Ortiz 2000). Ashouri et al. (2001) have shown that GMIR potatoes designed to resist Colorado potato beetle (*Leptinotarsa decemlineata*) had unexpected effects on populations of potato aphids feeding on the transgenic plants. In one transgenic line they studied, these effects could have had a tertiary impact on the spread of potato viruses. This work shows that even in a simple agricultural ecosystem, it is difficult to predict ecological perturbations caused by GM plants with simple monogenic insect resistance.

IR traits might affect the soil and wood decomposer cycle within plantations because the initial stages of decomposition in forest ecosystems often involve comminution of plant material by arthropods, especially mites (Edlin 1970). If the GM trait were adversely to affect this initial stage of decomposition then leaf litter and brash could break down more slowly, with unpredictable ecological consequences for arthropod and fungal components of the forest ecosystem.

Transgenic Fungal and Virus Resistance

Traits conferring general fungal and viral resistance have been inserted into tree species, mostly into fruit-producing varieties such as papaya, apple, and cherries (Table 1). Whilst virus resistance is unlikely to have an adverse impact on the biodiversity of plantations, it is possible that the introduction of generalized fungal resistance could affect decomposer ecosystems in plantations, although there is a large number of fungi involved in such processes in woodlands and it is likely that the traits would be overcome by at least some of the fungi present. However many saprophytic fungi are quite specialized in their choice of substrate, so there could be adverse effects on the diversity of macrofungi in GM fungal-resistant plantations.

Concern about the conservation of fungi has increased in recent years because there has been a significant decline in the abundance of many fungal species throughout Europe. Humphrey et al. (2000) found that mature stands of pine and spruce held the greatest diversity of fungi, and that clear felling with removal of deadwood was associated with significant reductions in fungal species. Of the 419 species they recorded in plantations, 157 were litter saprophytes. As the management of GM plantations might differ from that of conventional stands, impacts on fungal diversity may become an important aspect of monitoring.

QUALITY TRAITS

So far most research on changing the quality of timber has focused on varying lignin/cellulose ratios in deciduous woods such as poplars (*Populus* spp.) Wood from these GM trees would be better suited to the industrial processes used to recover cellulose for paper and board manufacture, potentially leading to reductions in the chemicals and energy needed for pulping, which in turn should reduce pollution from mills (Petit-Conil et al. 2001).

Little is known about possible effects of altering lignin and cellulose contents on palatability of GM trees to phytophagous animals, although experimental releases of reduced-lignin poplars appear to be no more susceptible to insect attack than are conventional poplars. Other trees with altered quality traits may, however, be found to behave in similar ways to hybrid agricultural crops, requiring more defense against phytophagous arthropods and fungus and virus attack. If such defense were to be in the form of increased agrochemical use, then the biodiversity value of these GM plantations might be lower than that of conventional plantations. Alternatively, it might be necessary to introduce multiple GM traits, such as insect, fungal, and viral resistance to combat damage.

Changing lignin:cellulose ratios may affect the strength characteristics of trees which could affect their wind firmness in plantations. This could lead to changes in how and where they are grown, or in their patterns of response to extreme wind conditions. Such changes could impact forest strategy by, for instance, encouraging more plantations in less exposed situations. There may implications for biodiversity inherent in such changes.

STERILITY AND OTHER BIOSAFETY TRAITS

Genetic modification is often used to manipulate tree species that are either native to the region in which they are to be grown or sexually compatible with native trees that are closely related. Trees are by nature long-lived perennials, and regulatory authorities are rightly concerned about genetic stability and gene flow from the transgenic varieties to native species. In some species, notably poplars and aspens (*Populus* spp.) and willows (*Salix* spp.), there is concern that transgenics may be able to propagate vegetatively, but most risk assessment has centered on gene transfer via pollen.

There has been a trend toward trying to engineer sexual incompetence into transgenic trees, either by disrupting pollen production mechanisms or by suppressing flowering, and therefore the production of seeds and fruits. If these measures were adopted commercially, plantations would be of trees producing neither pollen nor fertile ovaries. A major element of the woodland food web would be either unavailable or greatly reduced in these plantations.

The production of pollen, nectar, seeds, and fruits is an important factor in maintaining natural biodiversity in uniform single-species plantations of conventional trees, whether coniferous or deciduous (Palik and Engstrom 1999). In temperate regions, for example, coniferous plantations are crucial to the survival of several species of seed-eating birds (e.g., crossbills in Europe and Clark's nutcracker in the U.S.) and some mammals, such as red squirrels in Britain and the red treemouse in the United States. Specialist birds, such as the yellow-bellied sapsucker, depend on a range of conifer and deciduous tree saps and nectars at critical points in their breeding cycles (Tate 1973). In tropical regions, deciduous plantations often produce copious quantities of nectar and pollen that support a wide range of insects and the food webs associated with them. Honey bees often feed on deciduous hardwood plantation species, and in some areas provide a valuable source of income. There is therefore a conflict between the desire to enhance biosafety by suppressing sexual reproduction in transgenic trees, and the need to maintain biodiversity, and in some areas economically important activities such as plantation-based beekeeping.

The most obvious solution to maintaining biodiversity among sterile trees would be to plant mixed stands of transgenic and conventional trees, either in direct admixture or by planting blocks of different trees. Mixed-species stands are known to increase forest biodiversity by increasing structural complexity, but as Larsen (1995) points out, tree species for admixture should be chosen to support food web interactions by taking account of known co-evolutionary relationships. Plantations of this type should be more resistant to physical or biotic stress (Larsen 1995).

Because genetically engineered sexual incompetence will occasionally fail, there could be biosafety implications for mixed-species plantations if the species admixture included trees that were sexually compatible to transgenics. If the mixed species were sexually incompatible, risks could be acceptably low, and such mixtures could add to biosafety by further reducing vegetative propagation and pollen flow from GM trees that sporadically regain fertility.

GROWTH TRAITS

Transgenic traits designed to give faster growth have been suggested as a possible solution to improving productivity of biomass plantations and those where pulpwood is the primary goal. Such plantations could be advantageous to native biodiversity, especially if they were subjected to regular short-rotation coppicing favoring woodland flora and bird species that require a range of ecological successions within forests.

Even if biomass and pulpwood coppicing with regular fertilizer use were to result in species-poor ground flora, the temporal and spatial range of vertical structure produced could favor woodland flora and fauna, including bird species that require a range of structural successions within forests. However, these potential advantages could be offset by simplification of plantation food webs caused by high-growth GM trees that included pest- and disease-resistant traits.

RISK ASSESSMENT

There are serious concerns about introducing high growth traits and pest and disease resistance into transgenic trees, especially where the tree species already shows invasive tendencies. There are examples where non-transgenic conifers and deciduous trees have invaded natural ecosystems (for example *Hippophae rhamnoides, Pinus sylvatica, Rhododendron ponticum, Robinia pseudacacia,* and *Quercus ilex* in Europe, and *Syringa* in the United States). These invasions have often been from plantations into surrounding natural woodland. Research has shown that predicting invasiveness is very difficult, especially for long-lived perennial species like trees (Williamson and Fitter 1996; Manchester and Bullock 2000).

Risk assessment processes worldwide have not yet been able to predict with any certainty what impacts on native biodiversity might result from releasing transgenic perennial plants such as trees. The issue of gene flow has dominated the debate and has largely focused on attempts to measure *rates* of gene transfer (the question of "Does it happen?"), with little research on the *impacts* transgenes might have on fitness of recipient organisms ("Does it matter?"). This is especially difficult to predict in the longer term where long-lived perennials such as trees are involved. The key to predicting fitness lies in identifying the principle components of fitness relative to the organism in question and the habitats within which it lives. Muir and Howard (2001) have modeled impacts on fitness of a theoretical transgene that influences several fitness parameters simultaneously in a fish, Japanese medaka (*Oryzias latipes*). They show that, for a wide range of fitness values, transgenes conferring quite small increases in fitness could spread in medaka populations. Using a similar methodology, models could be developed for estimating impacts of transgenes (such as increased growth) on tree fitness, providing there are sufficient data available for identifying and estimating fitness components. A major problem with the modeling approach to fitness assessment of transgenic perennials lies in the difficulty of predicting the environments into which such trees might spread. Unless this can be done with some certainty, it will not be possible to estimate fitness components to populate a model.

If GM trees are ever to be used in plantation forests, it is likely that they will contain combined GM traits, such as altered timber quality with insect resistance. It could be very difficult to model the direct and indirect impacts on biodiversity of these GM multiple-trait phenotypes, even if the potential ecological impacts of each trait in isolation were known. In assessing risks from annual GM agricultural crops, it is possible to carry out comparative ecological studies over three or four years, such as the 'farm scale evaluations' of GMHT crops in the UK (Firbank et al. 1999; Firbank and

Forcella 2000), but with long-lived perennials such as trees, a predictive modeling approach may be the only realistic option if regulatory authorities are to make decisions on consent for release within a reasonable time-scale. Where the ecological relationships between trees and 'target' conservation species are known it may be possible to model impacts. An example can be found in the use of hybrid poplars by breeding golden orioles (*Oriolus oriolus*) in the UK, where the physical structure and phenology of the trees is crucial to breeding success. The critical factors in this ecological relationship are known (Milwright 1998) so transgenic poplars could be assessed for their suitability as golden oriole habitat.

The use of ecological modeling may improve the capacity of risk assessors to be able to predict biodiversity impacts, but comparison between transgenic and conventional plantations can only be made if models can be populated with quantitative data. To provide adequate data for risk assessment there is clearly a need for more research on the population dynamics of transgenic trees and the general ecology of plantations, especially forests populated by tree species that are currently the focus of transgenic and genomic development. There is a particular need for more research into the ecology of plantations in the tropics, where the relationship between forest trees and non-crop biodiversity is important for nature conservation and may be critical to the stability and productivity of future plantations, whether transgenic or conventional (Larsen 1995).

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Invasiveness of Transgenic vs. Exotic Plant Species: How Useful is the Analogy?

James F. Hancock
Karen E. Hokanson

ABSTRACT

Numerous ecologists and evolutionary biologists have incorrectly suggested that genetically engineered crops are analogous to exotic introductions. A growing body of evidence indicates that exotic species become invasive when they are introduced into a new area, where there are few to none of the natural constraints with which they evolved, and so they fill a new niche and their numbers explode. Most of the successful exotics are already good colonizers somewhere else and carry a whole syndrome of traits associated with weediness. This is very different from the situation facing transgenic forestry and agronomic crops. The crop antecedents are generally poor competitors outside the agroecosystem and carry few weediness traits. After the crop is engineered, it will not be removed from the complex array of natural constraints that currently faces it, and in most cases only one of those constraints will be removed by the addition of a new trait. In fact, it is much easier to predict the environmental risk of transgenic crops than an exotic introduction, as the level of risk in transgenics can be measured by evaluating the fitness impact of a single engineered trait, rather than a whole syndrome of potentially invasive traits. The risk of most transgene deployments can be effectively predicted by considering the phenotype of the transgene and the overall invasiveness of the crop itself.

It has commonly been suggested that invasive, exotic species can be used as models for evaluating the risk of release of transgenic crops (NAS 1987; Tiedje et al. 1989; Parker and Kareiva 1996; Marvier 2001). For example, Keeler (1998) states, "one set of data that can be used to understand what engineered organisms are likely to do is derived from the literature on introduced organisms. They are not genetically engineered, but they represent organisms that were introduced into communities of organisms which they had no previous experience."

We are all familiar with the 'environmental disasters' associated with the introduction of exotic species. In many instances, these species were intentionally introduced, such as *Rhododendron* in the U.K., pine in Australia, kudzu in the southeastern U.S., and purple loosestrife in eastern North America (Keeler 1988; Mooney and Drake 1986; Crowley 1997). Others arrived on their own, such as the Dutch elm disease and corn leaf blight in North America. The vast majority of introduced organisms perish or don't establish self-sustaining populations (Pimentel et al. 1989), but we keep being drawn to those that do.

CHARACTERISTICS OF INVASIVE SPECIES

So, what does make a species invasive? To answer this question, we first need to define what we mean by invasive. Probably the most common definition given

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is the ability to increase when rare; however, all successful species meet this criteria. Crowley (1997) suggests that invasive species should really be called "problem plants," where the species has passed some threshold of abundance and someone is concerned. He suggests that to understand the population biology of an invading plant genotype, we need knowledge of the following: 1) abiotic environment, 2) the biotic environment, 3) interaction between biotic and abiotic environment, and 4) the year. In other words, the nature of invasiveness is a very complex situation.

Sarah Reichard recently published a series of papers presenting a framework for evaluating plant invasivenes (Reichard and Cambell 1996; Reichard and Hamilton 1997; Reichard 1999). Her decision tree is based on a predictive model derived from discriminant and regression analysis of a number of structural, life history, and biogeographical characteristics of introduced woody plants. The characteristics analyzed, most of which have routinely been implicated in association with invasiveness, included: native range, whether or not the species invades elsewhere, leaf longevity, polyploidy, reproductive system, vegetative reproduction, minimum juvenile period, length of flowering period, flowering season, length of the fruiting period, fruiting season, dispersal mechanism, seed size and seed germination requirements.

Of the woody plants that invaded the United States, Reichard found that 54% invade other parts of the world, 44% spread by vegetative means, most have shorter juvenile periods, and 51% have seeds that germinate without pretreatment, while only 3% have been introduced from other parts of North America and 1% are interspecific hybrids. Based on these results, Reichard developed a decision tree for acceptance of exotic woody species into North America, which begins with the question "Does the species invade elsewhere, outside of North America?" Two other important questions in the decision tree are "Is the species in a family or genus with species that are already strongly invasive in North America?" And, "Is the species native to parts of North America other than the region of the proposed introduction?" Other questions in the decision tree concern whether or not the species is a sterile interspecific hybrid, rate of vegetative reproduction, the length of the juvenile period, and germination requirements.

What her analysis indicates is that a high percentage of the exotic species that become invasive are already excellent colonizers somewhere else and their population size explodes when they are introduced into a new area where there are few to none of the natural constraints with which they evolved. This is very different from the situation facing transgenic forestry and agronomic crops. They will not be removed from the complex array of natural constraints that currently face them, and only a very limited number of these constraints will be removed by the addition of a new trait through genetic engineering. The array of factors regulating natural populations must be complex, as the introduction of single biological control agents have rarely had much of an impact on invasive, exotic species (Pimentel et al. 1984).

INVASIVENESS OF AGRONOMIC AND FORESTRY SPECIES

In fact, only a small percentage of agronomic and forestry crops are important weeds outside of agro-environments (Table 1). They rely on human disturbances to become established and rarely persist outside of specific habitats. Clearly exceptions exist, such as barley, rapeseed, and rice, but over 80% of all crop species do not persist

Table 1. Survival of North American crops in native environments

Non-persistent	Persistent/ non-invasive	Persistent/ invasive
Beet	Apple	Barley
Broccoli (Canola)	Asparagus	Rapeseed
Carrot	Blueberry	Rice
Cauliflower	Cranberry	Sorghum
Celery	Pear	Sunflower
Citrus	Poplar	Wheat
Cucumber	Spruce	
Cotton	Strawberry	
Eggplant		
Lettuce		
Maize		
Melon		
Onion		
Pea		
Peanut		
Pepper		
Potato		
Soybean		
Squash		
Sugarcane		
Sunflower		
Tobacco		
Watermelon		

(Source - Hancock et al., 1996)

in native environments. Crawley et al. (2001) have generated some excellent evidence of how poorly crop genotypes do in native environments whether they were genetically modified or not. When they compared the performance of transgenic and non-transgenic rape, maize, beet and potato in 12 native environments, the genetically modified plants were never found to be more invasive or persistent than their antecedents. In fact, all populations of maize, rape, and beet were extinct after 4 years, and only conventionally bred potatoes were left after 10 years (and only at one site). The transgenic rape and maize expressed tolerance to the herbicide glufosinate, the genetically modified sugar beet were resistant to glyphosate and the transgenic potatoes expressed either the insecticidal *Bt* toxin or pea lectin.

In his classic work, Baker (1965; 1974) associated a complex array of traits with colonizing ability including: broad germination requirements, short and long seed dispersal, discontinuous germination, long lived seed, vigorous vegetative reproduction, rapid growth to flowering, brittle propagules, continuous seed production, vigorous competitors, self-compatible, unspecialized pollinators, very high seed output, plastic seed production and polyploidy. When Keeler (1989) took Baker's weediness traits and compared the worst weeds to agronomic crops she found that serious weeds possessed an average of 81% of these traits, while random non-weeds had 59% and crop plants had 42%.

To date, eleven tree crops have been genetically engineered in the United States and tested in the field: apple, papaya, citrus, persimmon, pear, plum, pine, poplar, sweetgum, spruce, and walnut. When they are rated according to Baker's characteristics, they all fall well below the random non-weeds, ranging from 21 to 50% (Table 2). Poplar has the highest average of 50%, possessing the weediness traits unspecialized pollinators, variable seed dispersal distance, high seed production, seed production in many environments, vigorous vegetative propagation, brittle propagules, and polyploidy. However, they are outcrossing, have discontinuous seed production, short seed longevity, narrow germination requirements, discontinuous germination, are weak competitors, and grow slowly.

This suggests that in most agronomic and forestry crops, a whole syndrome of traits would need to be altered through genetic engineering to make them invasive; and Baker's list excludes most biotic controls. Because agronomic crops are often poor competitors in nature, their impact on native populations has also been generally limited due to introgression. There are numerous instances where hybridization with wild relatives has increased the weediness of the native species in agronomic fields through crop mimicry (Ellstrand et al. 2000), but there is little

Table 2. Weediness traits in transgenic trees that have been field tested in the United States.

Weediness trait	Apple	Papaya	Citrus	Persimmon	Pear	Plum	Pine	Poplar	Sweetgum	Spruce	Walnut
Broad germination requirements	no	no	no	no	no	no	no	no	no	no	no
Discontinuous germination	no	no	no	no	no	no	no	no	no	no	no
Long lived seeds (>5 years)	no	no	no	yes	no	no	yes	no	yes	yes	yes
Rapid growth	no	yes	no	no	no	no	no	no	no	no	no
Continuous seed production	no	no	no	no	no	no	no	no	no	no	no
Self pollinated	no	no	yes	no	no	no	no	no	no	no	no
Unspecialized pollinators	no	yes	no	no	no	no	yes	yes	yes	yes	no
High seed output	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Seeds produced in many habitats	yes	no	no	yes	yes	yes	yes	yes	no	yes	no
Short and distant seed dispersal	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	no
Vigorous vegetative reproduction	no	no	no	no	no	no	no	yes	yes	no	no
Brittle propogules	no	no	no	no	no	no	no	yes	no	no	no
Vigorous competitors	no	no	no	no	no	no	no	no	no	no	no
Polyploid (2n > 28)	yes	no	no	yes	yes	no	no	yes	yes	no	yes
% Weedy traits	28	28	21	36	28	21	36	50	43	28	21

evidence of crop genes effecting the overall fitness of a native species. Even though crop species have been planted among their progenitors for thousands of years, we are not aware of any report where the native fitness of the wild species was noticeably changed. When David Duvick (2000) ask a group of 20 experienced plant breeders if the introduction of conventional resistance genes has led to undesirable consequences with respect to the weediness of a crop or its relatives, the breeders knew of no example.

Predicting the Environmental Risk of GMOs

It has been suggested that genetically engineered trees pose significantly greater environmental risks than do genetically engineered food crops, because the genes inserted into trees are more likely to 'escape' into the wider environment (Campbell 2000). Plantation trees have been altered through breeding far less than have most agronomic crops, and as a result, are much more closely adapted to native habitats than are most crop species. However, most are not highly invasive in their native geographic range, and the transgenic derivatives and any native/engineered hybrids will be subjected to the complex array of factors that normally regulate the native populations. The bottom line in assessing the environmental risk of both transgenic trees and herbaceous crops is the nature of the transgene, i.e., how significant an impact will it have on the fitness of native populations should it escape.

In fact, it is much easier to predict the environmental risk of transgenic trees than an exotic introduction, as the level of risk in transgenics can be measured by evaluating the fitness impact of a single engineered trait, rather than a whole syndrome of potentially invasive traits. A unique genotype is not being introduced into an environment where its native constraints are removed. The species is already in that environment and we know how invasive it is. What we need to worry about is whether the addition of a single gene will increase its existing level of invasiveness to problem levels. An increase in vegetative reproduction, a decrease in the need for pretreatment requirements, or a shortened juvenile period could certainly raise red flags concerning invasive potential. But these alterations are currently no more likely to be accomplished through genetic engineering than they are through traditional genetic improvements. If these characteristics are the subject of any research efforts toward genetic improvement, they should bear close scrutiny for their effects on invasiveness of the species.

In some cases, the risk involved in the deployment of these transgenes can be efficiently evaluated through the concept of familiarity (Hokanson et al. 2000). APHIS now assesses risk based on the biology of the crop, the nature of the introduced trait, the receiving environment and the interaction between these. Knowledge of these factors provides familiarity, which allows decision makers to compare genetically engineered plants to their non-engineered counterparts. Familiarity allows regulators to efficiently assign levels of risk, without doing any additional experiments, when the phenotypic effects of transgenes closely mimic conventionally deployed or native genes. Hokanson et al. (2000), outline a number of examples where transgenic genotypes have similar non-transgenic phenotypes such as insect and virus resistance.

This approach was what was recommended by the first group of scientists who evaluated the environmental risks of transgenic crops. In the often cited paper of Tiege et al. (1989), they state "transgenic organisms should be evaluated and regulated according to their biological properties (phenotypes), rather than according to the genetic techniques used to produce them . . ." and "Long term experience derived from traditional plant breeding provides useful information for the evaluation of genetic alterations similar to those that might have been produced by traditional means, and such alterations are likely to pose few ecological problems." One of the major conclusions of the National Academy of Sciences report on "Field testing genetically modified organisms: Framework for decisions" was that crops modified by genetic engineering will pose risks that are no different from those modified by classical genetic methods.

The problem with using the concept of familiarity is finding genes of equivalent effect and strength in natural populations. Reasonable arguments can be made for many of the trangenes that are similar to conventionally deployed resistance genes, but numerous other engineered genes will produce phenotypes that are unique to the species or have broader effects than the native genes. Some of these transgenes are likely to be effectively neutral in the native environment, such as herbicide resistance, but others that alter reproductive potential and physiological tolerances may have much more significant impacts. Regardless, it is much easier to assign risk to transgenic crops than exotic species, as we can restrict our worry to the effect of one gene on the fitness of a species in the place it is already grown, rather than making guesses about the fitness of a whole species genome in a unique environment.

CONCLUSIONS

The patterns of spread of invasive, exotic plant species cannot be used to predict the environmental impact of transgenic trees and agronomic crops. While it is true that some transgenes will influence individual traits associated with invasiveness, numerous other natural characteristics of these species make single changes unlikely to substantially alter their competitiveness. Invasive species have almost always been introduced somewhere where they have few to none of the natural constraints with which they evolved, and so they fill new niches and their population numbers explode. In many cases, these species were already invasive in their original habitats. This is very different than making a single change in a species already with multiple controls. Most engineered species are poor colonizers and they will be grown in their original environment with its complex array of natural constraints. Normally, only one of these constraints will be removed by the addition of a new trait by genetic engineering. The risk of most transgenes deployment can often be effectively predicted by considering the phenotype of the transgene and the overall invasiveness of the crop itself.

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BREAKOUT SESSIONS

Proceedings of the First International Symposium on
Ecological and Societal Aspects of Transgenic Plantations,
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www.fsl.orst.edu/tgerc/iufro2001/eprocd.pdf

Instructions to Leaders

Each of five breakout topics will be discussed by a subset of meeting participants in two independent one-hour sessions, A and B.

These questions are proposed as guides. Focus on the questions your group considers most important. Please also identify additional issues and priority areas for research.

Time is short. Please manage your time carefully so the group does not spend all its time on a small technical issue. Work closely with your recorder to take notes on important points. You will be asked to present the results of your session to the main group, and summarize them in written form for the proceedings (1–2 pages).

BREAKOUT 1 — SOCIAL/GLOBAL CONTEXT

A) How can plantation forests play a role in the sustainable production of wood and fiber to meet human needs? How can the use of GM trees in plantation forests contribute toward this goal or detract from this goal?

B) How is it ethical or unethical to use GM in plantation forests? If unethical, why (relative to conventional breeding, hybridization, and exotic tree species)?

C) What are the most urgent research needs to address scientific and public concerns? What are the pros and cons, goals or limitations of a moratorium on field and/or laboratory research?

D) In what specific ways are regulations for research and deployment of GM trees in the USA adequate, excessive, or in need of fundamental redesign with respect to the goals of both protecting the environment and enabling socially desired technical progress? What changes would you recommend?

BREAKOUT 2 — BIOLOGICAL CONTEXT/ BIODIVERSITY

A) How might GM trees that are herbicide resistant, insect resistant, sterile, or have modified wood have negative or positive net impacts on biodiversity at the stand level, landscape level, and/or global level? Is a broad conclusion possible and how is it useful? How do biodiversity implications differ for native vs. exotic species? What kinds of research are needed?

B) Assuming that GM trees in forestry will be used largely in intensive plantation systems, usually in conjunction with clonal propagation, how are the ecological issues that GM plantations present significantly different in magnitude than those already inherent in plantation systems (e.g., exotics, hybrids, intensive breeding, short rotations, intensive silviculture)?

C) What represents adequate testing and deployment for GM trees grown on a 5–15 year rotation? How does this depend on species, growth rate, propagation method, and culture environment?

BREAKOUT 3 — INVASIVENESS/ WEEDINESS

A) How is the commonly made analogy between GMOs and intentionally introduced, invasive exotic species a useful one, or a misleading one, considering the relative magnitude of their biological risks and potential for unpredictable impacts on the environment?

B) What kinds of GM traits, if any, are expected to lead to increased weediness, invasiveness, or dysgenesis? What are the pros and cons that all GM trees, because of their method of creation, be considered potentially invasive until proven otherwise via experimentation?

C) Can the potential ecological risks for invasiveness be predicted with high reliability from knowledge of the genetic changes imparted without the need for long-term (multigeneration?) field trials to assess invasiveness (e.g., for domestication traits like short stature or reproductive sterility).

D) For what kinds of GM traits, in what species and environments, are fertility reduction systems highly desirable? How effective must fertility reduction systems be (stability, efficiency), when needed, to give acceptably low environmental risks, and how should this be established? What constitutes acceptably low risk?

BREAKOUT 4 — WOOD MODIFICATION

A) What are the goals of wood modification? How do GM goals differ from those of conventional breeding?

B) What concerns posed by trees with GM wood are greater than those of genetically novel trees produced during conventional breeding (families, clones, hybrids, provenances)? What represents adequate testing and deployment for GM trees with modified wood grown on a 5–15 year rotation?

C) What are expected changes to nutrient cycles or trophic interactions with trees possessing GM wood, either inside or outside of plantations, and are they greater than those normally associated with variations in intensive plantation silviculture?

BREAKOUT 5 — BENEFITS AND SAFETY OF PEST MANAGEMENT APPLICATIONS

A) Under what circumstances can insect resistance that results from one or few types of transgenes (e.g., Bt), be considered sustainable in plantation forestry? Can transgenic systems be considered sustainable, even if specific genes are not (e.g., sequential uses of different transgenes)? In what kinds of plantation systems and species, if any, is major gene insect resistance an acceptable option?

B) What non-target effects of pest resistance transgenes on insects and soil organisms, within or outside plantations, are likely to be great or modest (assuming tissue-specific promoters are employed)? How will they compare in magnitude to other impacts from intensive silviculture of plantation forests (variation among species and genotypes, weed control, density control, fertilization)?

C) Are herbicide resistant trees expected to have significant economic or environmental benefits? How can they be managed to provide healthier soil and aquatic systems than available with alternative means for weed control, as well as provide economic benefits?

Proceedings of the First International Symposium on Ecological and Societal Aspects of Transgenic Plantations, S.H. Strauss and H.D. Bradshaw, eds. College of Forestry, Oregon State University, 2001. pp. 197-198. www.fsl.orst.edu/tgerc/iufro2001/eprocd.pdf

Summary of Breakout Session 1A — Social / Global Context

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We began by considering question (C), what are the most urgent research needs to address scientific and public concerns? Next, we considered the question, what are the general goals, transgenic or not, related to forestry, from a societal point of view?

The group listed the following as included in society's goals for forests: more environmentally friendly ways to produce wood and fiber; increase and provide more efficient and environmental friendly ways to produce biopolymers; human welfare, including economic and social well being; pursuit of fundamental scientific knowledge; and enhancing the opportunities for people to contact nature.

More specification, in terms of more environmentally friendly ways to produce wood and fiber, one would focus on: faster breeding; increased carbon sequestration in forests as part of the production of wood and fiber; improvement in wood quality; phyto-remediation; and understanding supply and demand for timber products.

Societal considerations arise from these goals, and include: learning what are present public concerns; understanding what the public ought to know (creating an informed public); learning to what extent the public is informed; determining who benefits from the use of biotechnology for trees, who owns the inventions and property, and who bears the burdens; how to deal with public concerns about uncertainty.

Societal uncertainty is of three kinds: (1) uncertainty arising from how much one can trust what scientists, corporations, government agencies and non-governmental organizations say; (2) uncertainty due to lack of scientific understanding; and (3) intrinsic stochastic properties and variation in trees and forest and plantation ecosystems.

These societal considerations lead to a suggestion for specific research programs that include: ethical, legal and social issues (ELSI) programs for forest biotechnology—a funded research program based on prior ELSI programs. This would be a standard research program, with requests for proposals, and investigator-driven research. There would be government funding of research by scientific and other experts. ELSI also include public involvement and the development of educational, curriculum materials.

In addition, research ought to be done to establish guidelines to determine risk and to determine how to do risk assessment specifically for biotechnological modifications of trees.

And there is a need to understand human aspirations regarding forests, and to understand these beyond what one learns typical from public opinion polls as what the public believes. An understanding of human aspirations for forests also goes beyond but encompasses the specifics of forest biotechnology.

Third, research is needed on how to involve public decision-making related to biotechnology.

Fourth, ecological research is needed to understand forest plantations as ecosystems, in regard to such qualities as biological diversity within plantations, the potential and limits of plantations to support specific endangered or threatened species, and to serve as habitat for biodiversity characteristic of a forest type.

Proceedings of the First International Symposium on Ecological and Societal Aspects of Transgenic Plantations, S.H. Strauss and H.D. Bradshaw, eds. College of Forestry, Oregon State University, 2001. pp. 199-200. www.fsl.orst.edu/tgerc/iufro2001/eprocd.pdf

Breakout Session 1B — Social /Global Context

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Starting note: It was decided not to address question 'D' in relation to the regulation of transgenic trees in the United States, as this was a very detailed point. The bullet points indicate the main discussion points raised in relation to each question.

Question A. How can plantation forests play a role in the sustainable production of wood and fiber to meet human needs? How can the use of GM trees in plantation forests contribute towards this goal, or detract from this goal? Where will the wood come from if there are no plantations?

- Existing (wild) forests will be spared.
- Plantations contribute to *global sustainability.*
- Is demand growing? (There was some disagreement about how much.)
- Plantations will allow increased production, if it is needed.
- GM needed? (No consensus). The distinction of 'GM' from other forms of tree biotechnology is probably artificial in relation to the major issue of plantations in general.
- *Ownership* of GM trees will be the big issue, especially in developing countries, or on plantations not owned by big corporations, i.e., who will plant them?
- Who benefits will also depend upon the traits the trees are modified with, as well as other details e.g., the locality of where they are planted.
- There will probably be less opposition to GM plantations if it is not only big corporations who benefit. For GM plantations to be accepted, the benefits must be seen to accrue to local populations, 'consumers' and the environment.

Value of remaining forests? That is, merely because they are no longer needed for wood supply, does not mean they will automatically be protected, especially if they lose value.

If the issue of GM trees adversely affects public attitudes to plantations in general, that could be a big set-back to global sustainability.

There is huge variation in trees in general, which can be utilized, but not in all species all of the time. To extend the use of trees there is no alternative in some cases other than to genetically modify them, especially in extreme situations—such as reducing desertification, or in restoring salty or polluted soils.

Question B. How is it ethical or unethical to use GM in plantation forests? If unethical, why (relative to conventional breeding, hybridization, and exotic tree species)?

Whose ethics? Definitions?

- If the GM trees are deemed 'safe' and bring public or environmental 'good', then they are by definition 'ethical'.

- Long-term benefits are ethical.
- *Ownership* is again a critical issue, especially if the benefits accrue only to big corporations or remote government agencies, etc.
- Global and local public benefits must be widely perceived.
- *Risks* and *Benefits*—the situation must be avoided where profits and benefits are privatized, while the risks are socialized, i.e., society has to carry to costs of any errors or problems, while the benefits are not widely felt.
- The focus should be on forestry needs / needs which trees can help, then identifying the most appropriate solutions, i.e., GM should not be the primary issue.

Question C. What are the most urgent research needs to address scientific and public concerns? What are the pros and cons, goals or limitations of a moratorium on field and/or laboratory research?

Many valuable R+D projects were identified, which would be widely appreciated as in the public good (as below), and no fundamental objections were raised:

- GM trees with improved productivity probably offer the most important overall social and environmental benefits at the global level. e.g., improving the photosynthetic efficiency of selected tree species.
- Use GM to produce trees for combating environmental degradation, especially desertification, growing soil salinity in many areas and detoxifying contaminated waste sites. The benefits of GM trees do not have to be restricted to plantations!
- Trees resistant to the impacts of global warming are needed, e.g., drought-resistant trees—even out of desert boundaries, drought problems are increasing in many areas.
- Resistance to exotic diseases is needed in many cases. There are some well-known examples, but there may be others in future.
- Produce GM trees better suited as alternative energy sources to fossil fuels, e.g., trees with increased lignin content would be especially valuable, especially in developing countries, where fuel wood is a major need.

More industry-orientated goals (below) were also considered as offering legitimate benefits, but might be a ‘harder sell’ if proceeded with in isolation to projects of more obvious social benefits, as listed previously.

- BioPharming with GM trees, e.g., production of pharmaceuticals in rubber latex.
- More rot-resistant trees (during growth or as timber?).
- Trees resistant to more environmentally benign herbicides.
- Trees with reduced lignin content, or other properties which make processing easier, or improve/maintain wood quality while simultaneously improving productivity.

A global and local view of the problems, alternatives, and costs is needed in each case:

- Marketing may be needed.
- Scientists should show leadership, independence, and clarify choices on the matter of GM trees. If we feel as a scientific body that the benefits of GM trees can be gained safely, then we should say so, but care must be taken not to slip into giving merely commercial opinions [the boundary is probably a personal one].

The IUFRO Tree Biotechnology group could organize a number of working/advisory sub-groups to explore more carefully the requirements and feasibility of particular project areas (as previously) or on particular issues.

But . . . some problems and public concerns cannot be addressed by experiment and research, however!

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Ecological and Societal Aspects of Transgenic Plantations,
S.H. Strauss and H.D. Bradshaw, eds. College of Forestry,
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Summary of Breakout Session 2A — Biological Context /Biodiversity

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The question of how might GM trees for herbicide or insect resistance, or modified wood characteristics, etc., have negative or positive net impacts on biodiversity at the stand, landscape, and global level, was the primary question put to the group. This is a large and perhaps all-encompassing question, and the group had three main discussion points. First, the improved productivity added by GM trees/traits, if significant, could reduce local pressure on native wild forests. However, this may not be generally true, as wild forests may be providing other commodity values and may not be accessible for such forest management options. Second, it was clear that we need to focus in on the specific trait / scenario of the GM stand to evaluate what level or function of biodiversity we are affecting. Effect of any type of GM plant/tree or stand on local 'biodiversity' is too large to be helpful on the specific organism interactions that may be under question. Furthermore, it is likely that most of the interest will be on the effects of GM trees and stands on local surrounding ecosystems (i.e., populations of related or unrelated species), rather than within GM stands. Biotechnologists and tree breeders will of course be interested on the performance of the trait and the stand, but this was considered of less interest compared to the larger question on the ecological and social concerns being expressed.

The question of how do biodiversity implications differ for native vs. exotic species that may undergo GM transformation, was also put to the group. In general, it was expected to be that the use of exotics would be of less concern or impact, on biodiversity, than with native species. Reasons for this, were due to the likely reduction of cross pollination/contamination with related wild species.

What kinds of research are needed to address more of these concerns, before there may be more scientific and public acceptance? The group thought it is important, again, to be specific on what types of GM traits are being proposed for study or release. For example, those that kill organisms, modify internal structures/chemistry, etc, will all require much different types of investigation. GM ecological impact studies, which need to be in place prior to deployment on commercial scales, should consider the many of the protocols currently present in crop research.

How are the ecological issues that GM plantations present significantly different in magnitude than those already inherent in plantation systems? The group thought that there is not much difference and it is still primarily a question of how biodiversity is changed at the landscape level by how we manage plantations at this level. Although the specific GM trait in question may have a relatively smaller impact, there are nevertheless ecological issues that need to be considered. Research, therefore, could examine the effects of non-GM plantations on current landscape level biodiversity. Specific traits and specific organisms and populations could be targeted to evaluate evaluate effects (e.g., gene flow) of non-GM traits (or some markers). This may allow us to make inferences to GM tree stand impacts, without larger scale GM trait research.

What represents adequate testing and deployment for GM trees grown on a 5–15 year rotation? There appears to be two issues: 1) testing the internal performance of the GM traits in various lines, and 2) ecological impacts of the GM populations on adjacent wild populations. No single time frame was deemed appropriate as results will be evaluated, refined and re-evaluated over time and probably by a larger groups of people (i.e., an adequate outcome rather than length of time). Again, this will be trait and situation specific. In terms of ecosystem evaluation, may need to look at entire rotation time, plus more! Continued monitoring will likely be necessary until proven no longer needed.

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Summary of Breakout Session 2B — Biological Context /Biodiversity

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Question A. How might GM trees that are herbicide resistant, insect resistant, sterile, or have modified wood have negative or positive net impacts on biodiversity at the stand level, landscape level, and/or global level? Is a broad conclusion possible and how is it useful? How do biodiversity implications differ for native vs. exotic species? What kinds of research are needed?

Positive:

- Species restoration
- Positive influences on biodiversity and environmental integrity, if replacing annual crops with perennial crops.

Negative:

- Introduction of exotic species may (or may not?) be accelerated by use of GM trees.
- For biosafety reasons, there may be reasons that deployment in exotics may be greater.
- GM trees may mitigate *or* increase potential for invasiveness.

It depends:

- If perception is that it benefits the public, concerns about environmental impact and unknown will be reduced.

Research needed:

- Baseline characterization (ecology of non-GM plantations, indicators, conservation targets and their food webs, outcrossing):
- (Alternative) Direct experimentation on research plots
- How many clones needed to be deployed?
- How do we deploy different types of management under different conditions (e.g., riparian, soil characteristics)?
- Research to support policy question regarding where could/should GM be deployed
- Monitoring for movement of gene flow, movement of exotics, diversity, etc.
- Quantify net diversity change resulting in change in forest condition from GM trees.

What characteristics could lead to:

- Catastrophic outcome (e.g., influence on endangered species)
- Population effects on characteristics of juvenile plants.

What are the implications of large areas in monotypic, genetically simple forests? How is natural gene flow influenced by use of transgenic plantations? How do GMOs influence ecosystem processes?

Question B. Assuming that GM trees in forestry will be used largely in intensive plantation systems, usually in conjunction with clonal propagation, how are the ecological issues that GM plantations present significantly different in magnitude than those already inherent in plantation systems (e.g., exotics, hybrids, intensive breeding, short rotations, intensive silviculture)?

In many ways the issue is not GM trees but clonal forestry.

Question C. What represents adequate testing and deployment for GM trees grown on a 5–15 year rotation? How does this depend on species, growth rate, propagation method, and culture environment?

It depends on what level of risk the society is willing to accept (distinguish between risk and meaningful risk)—needs to consider both the magnitude of the consequence and the probability of its occurrence. Risk will be higher for traits that are favored by natural selection (especially of juvenile plants), possibility of introgression into wild population, characters that influences multiple traits. Testing could be relatively short if effects of traits are likely to be reversible, assuming mechanisms to withdraw use at a later time.

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Ecological and Societal Aspects of Transgenic Plantations,
S.H. Strauss and H.D. Bradshaw, eds. College of Forestry,
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Summary of Breakout Session 3A — Invasiveness / Weediness

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A) Is the commonly made analogy between GMOs and intentionally introduced, invasive exotic species a useful one, or a misleading one, considering the relative magnitude of their biological risks and potential for unpredictable impacts on the environment?

The general consensus of the group was that the analogy is misleading. A single gene addition to a species already growing in an area is not the same as the introduction of an exotic whole organism. However, the group felt that the analogy is useful in identifying those traits that make species invasive.

B) What kinds of GM traits, if any, are expected to lead to increased weediness, invasiveness, or dysgenesis?

The group felt that dramatic alterations in physiological tolerances such as drought or stress tolerance could lead to increased weediness, along with large changes in germinability and dormancy of seeds. But, it was pointed out that physiological trade-offs (pleiotropy) often occur in conjunction with these types of alterations that negatively impact on other fitness traits. The group was split on the risk of GM pest resistance. The environmental effects of GM resistance genes depend on how many species are controlled, whether phenotypically similar types of native resistance exist and how fast the pest evolves.

C) Can the potential risks for invasiveness be predicted with high reliability from knowledge of the genetic changes imparted without the need for long-term (multigeneration?) field trials to assess invasiveness.

The group consensus was that long term trials can often be avoided if we have thorough knowledge of the biology of the species (its invasiveness) and the nature of the inserted gene. The group also felt that critical information on establishment and growth characteristics is often provided in the initial short-term trials.

D) For what kinds of GM traits, in what species and environments, are fertility reduction systems highly desirable?

The group felt that it depends on the characteristics of the species, but fertility reduction should be incorporated along with any trait that will significantly impact on a species invasiveness, particularly if plantations are adjacent to native strands. The group was most concerned about dramatic changes in stress tolerance and the stacking of resistance genes in already invasive species. The risk of single gene GM pest resistance was thought to be dependent on the engineered species and its environment. Most alterations of growth and development were not considered to be great risks, as they were thought to have negative fitness tradeoffs (as do many of the resistance genes). Herbicide resistance was considered to be neutral in the natural environment. The point was made that we need to think globally; decisions on fertility reduction should be made by considering all the places in the world a GM species might be introduced.

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Ecological and Societal Aspects of Transgenic Plantations,
S.H. Strauss and H.D. Bradshaw, eds. College of Forestry,
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Summary of Breakout Session 3B — Invasiveness / Weediness

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A) Value of the Analogy

The session attendees agreed that the analogy between GM trees and introduced invasives was a poor one and that an *a priori* assumption of treating a GM tree as an invasive is not warranted for many reasons. Chief among those reasons that was cited is the knowledge about and behavior of the genetic background of engineered trees and the low likelihood of the modification initiating all the features that confer weediness.

It was also agreed, however, that the analogy does guide important questions that are valuable to ask of any GM tree in a regulatory context, in design of the transgenic tree, and in field trial design. The traits that confer weediness that were listed in the presentation earlier in the day provide a checklist or a decision tree with which to assess if the modification may alter key traits and if action must be taken.

B) Which traits?

The attendees agreed that traits that might alter sexual or vegetative propagation in any way are of primary concern as were any traits such as growth and resistance that may provide a selective and competitive advantage to the modified tree.

There was discussion if one can assume that pest or disease resistance could confer sufficient advantage that a tree might be invasive. There was some disagreement about whether there were cases in which a single pest or class of pest provided the constraint against weediness. This question appears to be one for future investigation or consideration.

While it was broadly agreed that GM trees should not bear a presumption of weediness, whether a specific trait allows a tree to occupy a new ecological niche is highly dependent on context. It was repeatedly raised that what was true of a particular tree in one ecosystem or culture context may not be true in different environment.

Sterility was a major focus of discussion with most participants in clear agreement that if a tree is sterile and incapable of independent vegetative propagation, invasiveness is highly unlikely.

C) Risk Prediction and Testing.

Participants agreed that there is considerable risk in extrapolating the results of experimentation in closed systems with the transfer of those trees to open environments and even among different open environments. Experiments and trials must be explicitly designed and monitored to assess increased invasiveness or competitive advantage of the GM tree.

Though there was agreement that risk could not be accurately predicted, the participants expressed that the combination of many risk mitigation strategies could bring risk to not only acceptable levels but to levels that would require only short-term testing. Those strategies include:

- Engineered reduced fitness (e.g., short height)
- Engineered sterility
- Redundant engineered mechanisms for sterility
- Active and adaptive management
- Monitoring protocols and metrics for invasiveness.

D) Fertility reduction and risk.

This question did not stimulate a great deal of discussion. There was the widely held view that there can not be such a thing as zero risk. To the question of how effective must fertility control be, the answer seemed to be “as effective as it can be.” As with other issues, the question is highly dependent upon trait and context.

It was pointed out that control of weediness via outcrossing could also be through the design of complex constructs that reduced the chance of productive transfer and recombination.

The discussion of acceptable risk appeared to be beyond the scope of the dwindling time of the breakout session. Participants agreed that risk is a function of the probability of invasiveness as well as its consequence. Some participants agreed that the more important question is not to determine the consequences at a time of such little data but to ask what are the standards that we use to describe those consequences, e.g., environmental standards as well as social and economic descriptions of consequences.

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Summary of Breakout 4A — Wood Modification

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A) What are the goals of wood modification? How do GM goals differ from those of conventional breeding?

Discussion: The goals for wood modification through genetic engineering include the following traits:

- lignin content
- cellulose content and quality
- fiber length
- fibril angle
- wood density
- rot resistence
- number of knots
- wood extractives

General consensus of the group is that the goals of wood modification through GM are no different from those of conventional breeding. GM and conventional breeding work toward the same goals which are tailored to product needs (e.g., pulp and paper or solid wood). Major differences, however, are as follows:

- GM can provide faster gains (as opposed to long breeding cycles)
- GM can increase precision of the modification (as opposed to conventional crossings)
- GM can create higher degrees of variation, exceeding those achieved by breeding
- GM may be the only means for wood modification when conventional breeding is not feasible (e.g., in certain parts of the world, for certain species, or for certain traits that are naturally present, such as engineering S lignin in conifers)
- GM is an important research tool to advance our fundamental knowledge. Transgenic trees have proven to be a powerful tool in recent years to address basic questions.

The group feels that it is inappropriate to separate GM and conventional breeding approaches for comparison in considering tree improvement programs. The group agrees that GM and conventional breeding approaches complement each other and should be used together. This has been the case in many studies where conventionally bred elite clones are used for further improvement by GM.

B) What concerns posed by trees with GM wood are greater than those of genetically novel trees produced during conventional breeding (families, clones, hybrids, provenances)? What represents adequate testing and deployment for GM trees with modified wood grown on a 5–15 year rotation?

Although GM offers many advantages over conventional breeding (see discussion in A), there are also concerns surrounding GM wood. The major issue is risk of side effects, including unknown public hazards, unknown trophic effects, unknown below ground effects on nutrient cycles and carbon sequestration etc. However, it was pointed out that none of these concerns is unique to GM trees. It was suggested that GM trees with modified wood properties might gain easier public acceptance as the process would mostly likely involve plant genes. Using non-plant genes seems to cause uneasiness among the public. The group feels that whether using non-plant genes in GM research bears greater risk than using plant genes is unknown, and was not convinced that GM wood would gain more public acceptance. Moreover, engineering of rot resistance or cellulose biosynthesis will still likely involve the use of non-plant genes.

Discussion regarding adequate testing and deployment of GM trees with altered wood quality suggested that the testing clearly has to go beyond evaluation of the targeted wood properties. Adequate testing may need to include evaluations of whole tree growth and development, crop vulnerability and ecological safety. Environmental factors also need to be taken into consideration, hence GxE testing may need to be conducted at multiple sites and times. There also needs to be an adaptive management plan allowing flexibility to deal with new information or unforeseen developments. Again, we felt that these issues are no different from the clonal plantation practices. As to the duration of the testing, it is an important and practical issue facing researchers, tree growers (forest industry), regulatory agents and public (with different risk consideration). Industry may not invest or be interested in GM trees at all if full rotation testing is required (not time-saving). However, short range, such as 5-year testing may not be acceptable to the public and regulatory agents. The appropriate length of testing may need to be determined according to the end use of the GM wood. For example, half- or quarter-rotation testing might be adequate for short-rotation wood crops for pulp and paper production, but testing until full rotation age might be necessary for solid wood applications.

C) What are expected changes to nutrient cycles or trophic interactions with trees possessing GM wood, either inside or outside of plantations, and are they greater than those normally associated with variations in intensive plantation silviculture?

Changes to nutrient cycles or trophic interaction certainly are of concern with plantation trees possessing GM . However, when compared with intensively managed clonal plantations, the group failed to identify any significant difference. The GM plantations are likely to be managed the same way as clonal plantations (i.e., fertilization, irrigation etc). However, the issue bears complexity associated with the target traits, degree of variation, and species, and should be dealt with on a case-by-case basis. Considering that these are not issues unique to GM trees but are also common to field GM crops, the group feels that GM researchers working on tree improvement are held to a higher standard of accountability than agonomists using GMO.

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Summary of Breakout Session 4B — Wood Modification

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This session set about to address the following three questions, and to iden tify additional issues and priority areas for research.

A) What are the goals of wood modification? How do GM goals differ from those of conventional breeding?

The goals of wood modification (be it by GM or conventional breeding) fell into two categories:

- Basic science goals—a tool for research into wood properties. Examples include
    - candidate gene testing for QTL association studies
    - determine effect of modified wood properties on end uses (e.g., pulping)
    - determine impact of changes on one wood component on the quantity/properties of another wood component (e.g., lignin and cellulose).
- Applied goals—end-use properties are the drivers here. Examples include
    - modification of the usual suspects: lignin, cellulose, chemistry (extractives / secondary metabolites)
    - modification of morphology and development
    - production of novel products.

The goals of GM and conventional breeding were viewed as being the same, but the means to the end, the rate of change, and the end product may be radically different. In general, it was agreed that directed modification was a greater possibility with GM and that the rate of change could be faster with GM (a shortcut to modification relative to conventional breeding). Furthermore, it was agreed that GM has the potential to extend the range of modification beyond the 'natural range' of variation. For example, it is theoretically possible to modify gymnosperms by GM such that they produce syringyl lignin, which is not normally found in gymnosperms. Alternatively, GM angiosperm trees could be modified to produce entirely guaiacyl lignin, which has not been reported in natural populations of these trees.

Research priorities: identification of genes involved in wood formation, identification of promoters to drive gene expression during specific times in wood formation, association studies to identify loci important in wood formation/properties.

B) What concerns posed by trees with GM wood are greater than those of genetically novel trees produced during conventional breeding (families, clones, hybrids, provenances)? What represents adequate testing and deployment for GM trees with modified wood grown on a 5–15 year rotation?

The short answer to former question is: "It depends". The potential problems associated with the growth, development or perception of GM trees that were identified in this session were as follows:

- Trees have characteristics that extend beyond the "normal" range of natural variation; although, it remains to be determined what the "normal" range is for many traits.
- Unforeseeable problems in dealing with trees with "extreme wood" - difficult to deal with the unexpected.
- Impact of pleiotropic effects—what else might be affected by the modification?

It is important to point out that it was generally agreed that the concerns with respect to GM trees might be less than those associated with conventionally bred trees, for the following reasons:

- One can 'track' the introduced gene easily.
- Single gene introductions, or, in the instance where multiple genes are introduced, there is a limit to the number of genes, and the genes are known.
- The introduced genes and their direct effects are well-characterized and known.

In this session, the following points were made relative to what constitutes adequate testing of GM trees:

- Epistasis analysis is required, but this might be facilitated by GM as one can 'track' the introduced allele easily.
- The space and time required for testing are unlikely to be different from those required for conventional breeding, but, GM testing is likely to be more extensive. NOTE: Following from this point, it was asked if it was really necessary to have more extensive testing of GM trees. General consensus was that it was not really necessary and that tests equivalent to those used for conventionally bred trees were likely to be substantial enough—at least from a scientific and industrial perspective.
- There are two imperatives that were identified that drove testing: biological (including everything from plant reproduction to interaction with the environment, which is considered below) and industrial. It is clear that trade-offs will be needed on both sides—as is the case for pharmaceuticals, for example. This is best dealt with using current risk assessment protocols and incorporating them with "adaptive management" approaches.
- Research priorities: epistasis analysis, development of risk assessment protocols for GM trees, field trials.

C) What are expected changes to nutrient cycles or trophic interactions with tree possessing GM wood, either inside or outside of plantations, and are they greater than those normally associated with variations in intensive plantation silviculture?

As for question B above, the answer to this question is "It depends". The supposition is that wood modification would impact the following aspects of tree biology:

- resource allocation might change
- post-harvest biotic interactions might change
- inadvertent susceptibility to certain pests or pathogens may arise due to the modification.

However, it was noted that these changes would not be unique to GM trees relative to trees with wood modifications through conventional breeding, but the extent to which these changes may occur might differ, particularly as the changes to wood properties become more and more "extreme".

It was felt that increased invasiveness of trees with modified wood properties was highly unlikely. The reason for this is that trees that are investing resources into wood production are likely to do so with a trade-off to reproductive development. That is, from an evolutionary perspective (i.e., not a tree health perspective), trees with modified wood are likely to have a lower fitness and, if anything, be less invasive. This is a point that needs to be emphasized to those concerned with the invasiveness of forest trees. Again, the issue here is not unique to GM trees and also applies to trees which have been generated through conventional breeding.

While horizontal gene transfer is frequently raised as a concern in some quarters, it is not realistic to expect that modifying wood properties would increase the likelihood of this already rare occurrence.

There is a concern in some quarters that generating trees with improved wood properties/production will lead to intensification of clonal forestry and a change in management practices. It was felt that this was an issue that was not unique to GM trees and needed to be dealt with more broadly under the category of “plantation issues”.

It is clear that empirical data are needed in order to address question C. It remains to be determined how these data are to be collected for GM trees, but it was felt that the collection methods should no different from those already used in traditional breeding efforts. Furthermore, it was agreed that data collection should deal with GM trees on a trait-by-trait basis, and not generically.

It is important to note that one has greater control over the modified material when using GM. There is control during the process of producing the trees, which is laboratory-based. There is also excellent control at the level of the end-product, which can be readily and easily tracked. The features of GM are considered a substantial benefit when it comes to assessing and mitigating any risks that may arise with trees that have modified wood properties/production.

Proceedings of the First International Symposium on Ecological and Societal Aspects of Transgenic Plantations, S.H. Strauss and H.D. Bradshaw, eds. College of Forestry, Oregon State University, 2001. pp. 213.
www.fsl.orst.edu/tgerc/iufro2001/eprocd.pdf

Summary of Breakout 5A — Benefits and Safety of Pest Management Applications

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Tree genetic engineering for increased pest resistance represents a topic with a significant list of concerns from the public point of view. This field of research has also been the subject of numerous discussions among scientists. The questions provided in the book of abstracts were not answered specifically; instead, the group discussed a few ideas provided by the chairperson.

The first question was, Why use genetic engineering to control pests? The group discussed a number of reasons, and then selected the following as the most important:

1. Increased productivity—in the context of tree plantations, reducing losses will provide greater returns and increased quality.
2. Reduction of chemical uses—reduction of chemicals could also have a positive impact on biodiversity by preventing the destruction of non-target species.
3. Increased capability to respond to a specific pest—this aspect is important for maintaining biodiversity in the context of a major infestation by a specific pest.
4. Maintaining soil conservation—in this case herbicide resistance could provide an efficient way to prevent soil erosion.

The second question focused on the trait to introduce. Although this represents a case-by-case approach, some general conclusions can also be drawn (see 'to do list' below).

1. Could be simple and well known (e.g. Bt endotoxin)
2. Could be complex (metabolic engineering)
3. Materials that have a high turnover should be preferred.

Finally, the group discussed and created a 'to do list' of suggestions: In all cases the issues of environmental and economic viability should be prioritized. Once the economic needs are well established, solutions with current and biotechnical approaches should be evaluated. For each case, research on the impact on non-targeted species and potential effects on plant chemistry should be evaluated. It is also important to test the four reasons (proposed above) for using genetic engineering to control pests. In many cases, field trials are also needed to address specific questions related to issues such as recombinant protein turnover and weediness. Sterility should be viewed as an efficient approach to reduce the risk of gene movement from plantations with consequent risks for weediness or expanded non-target effects.

Proceedings of the First International Symposium on
Ecological and Societal Aspects of Transgenic Plantations,
S.H. Strauss and H.D. Bradshaw, eds. College of Forestry,
Oregon State University, 2001. pp. 214-215.
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Breakout Session 5B — Benefits and Safety of Pest Management Applications

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We began by discussing two questions that were considered central to the controversy over transgenic plants and relevant to potential pest management approaches in particular:

1. Is the use of non-plant genes to modify trees inherently problematic?

   The participants in the break out session expressed differing views in response to this question. Those who thought that this technology is inherently problematic cited its novelty and its difference from what happens in nature as the reason for their concern. Those who thought the use of non-plant genes in trees is not problematic pointed out that the occurrence of horizontal gene transfer across species boundaries is an analogous, naturally-occurring process, albeit it appears to occur at a very low frequency.

2. Are the risks of tree transformation with plant genes different than the risks of tree transformation with non-plant genes?

   The participants believed that the perception of the non-scientific public is that transformation with non-plant genes is more risky than transformation with plant genes. If this is in fact true, then scientists and biotechnologists need to be cognizant of this fact, especially when explaining their work and discussing its perceived risks with the public. In general, the scientists in the room thought that the actual risks associated with either type of transformation are dependent upon the specific function of the transgene, or are unknown.

The second topic we considered was the sustainability of single-gene transgenic insect resistance strategies (e.g., the expression of Bt toxin). We identified the nondurability of this strategy in the field as the major challenge faced by it, although this problem is not exclusive to the transgenic deployment of pesticides. Potential solutions to this problem include the pyramiding of multiple pesticide genes in individual plants, the inclusion of refugia in the field, and the precise timing of pesticide expression (e.g., during the months of greatest insect attack and/or in the most susceptible tissues). It was pointed out that in trees, the pyramiding of resistance genes could only be achieved via transgenic approaches because the long generation times in trees would make pyramiding via repeated breeding cycles impractical. Transformation, therefore, provides a special advantage over breeding for improving pest or pathogen resistance in trees. Additional challenges faced by pesticide-expressing trees include unintended effects on the trees themselves and non-target organisms in the environment, and the fact that the controversy over transgenics has created a particularly high burden of proof for the value of such projects. The sequential use of pesticidal transgenes was considered a sustainable approach for long-term management, particularly because this does not differ significantly from more conventional pest and pathogen management schemes. Transgenic plants expressing pesticides were considered most appropriate for species grown in short rotation plantations because the risk of transgene escape would be minimized in short rotations and because there would be an opportunity to deploy new genotypes at the end of the rotation if insect resistance had failed.

Potential non-target effects on insects and soil microorganisms are likely to depend upon the characteristics of the transgene and are likely to be minimized as advances in engineering technology make it possible to target gene expression to specific tissues and time periods. It is currently difficult to say how transgenic insect resistance is likely to compare to intensive management practices in terms of non-target effects because we have a poor understanding of the effects of intensive management or conventional breeding on microbes and non-target insects. As a consequence this was identified as an area in need of further research. A potential unintended risk associated only with transgenic plantations is transgene escape, although breeding projects founded on crosses between distant relatives certainly could introduce novel genes into wild relatives when the hybrid progeny are planted in new locations.

When considering the potential benefits of trees expressing herbicide resistance, we used poplar as an example case. In terms of economic benefits, herbicide resistant poplar would result in labor savings as well as cultivation savings (e.g., fewer herbicide applications and a reduced need for soil disturbance). Potential environmental benefits of herbicide resistant poplar include soil conservation, reduced water use due to reduced weed competition, and the use of environmentally benign herbicides. The only perceived risk associated with this technology was transgene escape. This was viewed as problematic because it might make it difficult to control wild plants with environmentally benign herbicides. Research needs in this area include assessment of the natural invasive tendencies of any species to be transformed, mechanisms for fertility control, and the development of a greater variety of benign herbicides.

Appropriate regulations will help reduce fears about transgenics and will guide environmentally sound deployment, but it is unlikely that such regulations will be adopted worldwide. In addition, during the course of the discussion the point was made that the current scrutiny applied to transgenic plants might prompt a similar scrutiny of conventional breeding for plant improvement.

Summary Views

Proceedings of the First International Symposium on Ecological and Societal Aspects of Transgenic Plantations, S.H. Strauss and H.D. Bradshaw, eds. College of Forestry, Oregon State University, 2001. pp. 219.
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Policy Perspective

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The objective of enlightened policies is to promote objectives that, in the broad context, should lead to improvement of the generate welfare, in cluding, but not limited to economic welfare. These objectives should are also appropriate for policies related to innovations in forest biotechnology.

In the economic realm, policies are usually designed to promote income, employment and economic growth. Policies focusing on promoting innovation, investments, the efficient use of resources and an equitable income distribution would generally be regarded as contributing to the general welfare. However, attention is given to activities and/or products that may generate negative externalities, e.g., air or water pollution, or unrecognized health and safety risks. These include negative externalities that may be associated with the introduction of biotechnological innovations, including transgenic trees.

Biotechnological innovations in forestry clearly have the potential over the long term of promoting enhanced economic well-being. They can lower costs, improve quality and make goods and services more accessible to humankind. Additionally, they can provide positive environmental services, including the provision of land restoration services to the rehabilitation of almost extinct species, such as the American chestnut. Furthermore, the evidence over the past several decades that wood harvested from plantation forests substitutes for wood that would have been harvested from natural and old-growth forests is compelling, despite the reluctance of some to acknowledge the evidence. Biotechnology can enhance this shift to planted forests.

However, innovations may also involve risks and uncertainties. In forestry, major concerns with transgenics tend to focus on the possibility of unplanned and negative impacts on the natural environment. In order to better understand the nature and magnitudes of these potential risks, a regulatory approach has been created for forestry in which USDA APHIDS bears the responsibility for determining the extent of the externalities that may be present and ultimately the acceptability of a forest transgenic innovation. Under this system various types of tests and trials are undertaken, including field trials, to determine whether the innovation should be allowed to move to commercial applications. The procedure accepts, rejects, or requires resubmission of the innovation for commercial use. It could well be that some transgenic innovations are essentially riskless, and should readily be accepted for commercialization, while others involve risks so great that prudence would suggest delaying the innovation until more information is available and, perhaps, ultimately rejecting indefinitely the commercialization of the innovation.

Finally, one may always ask if the procedures are adequate. However, it must be recognized that no amount of testing will remove all uncertainty. Ultimately the testing procedure requires an informed judgment of whether the testing is adequate and appropriate.

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Ethics Perspective

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This symposium is evidence that scientists working on tree biotechnology are off to a very good start in addressing controversial issues and ethical responsibilities. The papers and working group sessions have brought a number of key topics to the forefront. It is really quite remarkable that these topics should be addressed so thoroughly at this early stage in the development of the science. I would like to offer just a few concluding comments in reaction to what I have seen here.

First, scientists seem prone to two tendencies that cause problems both with respect to public receptivity toward technology and to the discharge of ethical responsibilities. One is a tendency to evaluate technology solely in terms of net outcomes. Clearly outcomes—costs, benefits and risks—matter a great deal. Yet we do not look with favor on others who are too quick to conclude, “the end justifies the means.” Even when the end *does* justify the means, we like to believe that others have given due consideration to values not easily characterized as subject to “trade-offs.” For example, there should be due consideration given to the intrinsic value of natural ecosystems, and affected parties should have an opportunity to participate in decision-making, and to give or withhold consent. It was distressing to see workshop groups moving toward trade-off rationalization after only a few minutes of discussion.

The other tendency is to analyze controversy in terms of a distinction between real and perceived risk. While it is true that people can and do misjudge either the likelihood or the degree of hazard that is associated with the use of biotechnology, it is also true that the source of controversy can lie elsewhere. There may be different value judgments being made about how to understand the normative importance of uncertainty, for example, or about the socio-economic consequences of using technology. One should be sure that others share one’s values before presuming that different judgments of risk can be attributed to a mistake about probability or hazard.

Although the capabilities of bioethics should not be overstated, including philosophers or others with training in bioethics throughout the research and development process for technology is one way to hold such tendencies in check. One would hope that at least four or five bioethicists attach themselves to the emerging field of tree biotechnology early on, and that they are welcomed and included both at scientific meetings and at fora, such as this one, where social, ethical and public issues are the primary topic of discussion. A good way to make this happen would be for a few far-sighted deans to create positions in bioethics within forestry or environmental science programs at their universities, and to provide support for publication and teaching on the ethical issues of tree biotechnology. And may I conclude with the hope that this remarkable beginning becomes a standard practice for the emerging field of tree biotechnology.

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Industry Perspective

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We extend sincere thanks to Steve Strauss and Toby Bradshaw for organizing this important symposium and inviting our participation. The potential benefits of forest biotechnology have been clarified and re-affirmed. Good progress has been made in developing a more integrated community view of ecological and economic opportunities.

The symposium has outlined important uncertainties and challenges in the future of forest biotechnology, with considerable emphasis on ecological concerns. Rather general discussions of ecological risks indicate a need for research focused on specific technology applications with careful attention to characteristics of the transgenic trees themselves; characteristics of environments in which transgenic trees might be deployed; and the design and expected effectiveness of risk reduction measures.

Several speakers have provided useful insights into social, economic, ethical, and regulatory issues associated with forest biotechnology. These issues require substantial and sustained attention even though the path forward is often unclear and potentially treacherous. The complex implications of forest biotechnology seem to require new approaches and unconventional partnerships such as those envisioned by the Institute of Forest Biotechnology.

We and others at the symposium have discussed the potential value of biotechnology to the forest products industry. It is clear that strategies and perceptions vary greatly among companies and stakeholders. In general, requirements for commercialization of forest biotechnology will include:

(a) Expectations of superior returns to shareholders with acceptable risk relative to alternative uses of capital

(b) Environmental performance will be maintained or enhanced

(c) Social and market acceptance issues have been evaluated thoroughly.

Further investments in R&D are critical to realizing the potential of forest biotechnology. An important economic hurdle is reducing costs associated with vegetative propagation of important softwood species such as loblolly pine. Accelerated research on ecological concerns and risk management options (e.g., flowering control) will be needed to satisfy environmental and social requirements.

Research organizations, both public and private, have essential roles and enormous opportunities in forest biotechnology. In the United States, inadequate government support for pre-competitive research is a significant obstacle to progress.

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Ecological Science Perspective

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It was widely accepted by presenters from a broad range of backgrounds that genetic engineering of plantation trees can offer some significant environmental benefits. These include reductions of pesticidal inputs, reduced pressures on wilderness areas arising from increased productivity of intensively managed plantations, and increased response capability to biological invasions. Whether these potential benefits can be realized will depend largely on whether potential risks can be managed. A common theme throughout many of the talks concerned the issue of scale: How can we extrapolate from short term experiments under controlled conditions to scientifically reasonable projections of long term consequences at the landscape level? This issue remains unresolved, and should be a major area of focus. Each person's approach to this question reflects, to some extent, the level of biological organization at which they commonly work. Molecular biologists often find that resolution of difficult scientific problems is achieved by deeper understanding of specific mechanisms, and by improved techniques for approaching intractable questions.

Ecologists, in contrast, often find that resolution of difficult scientific problems is achieved by recognizing which factors originally perceived as outside their unit of study are in fact exerting strong feedback on the system. These experiences color the extent to which biologists working at different scales trust that extrapolations from laboratory and small field studies to long term and landscape projections can be made. In some ways, however, these differences offer an opportunity, by identifying how differing approaches can best be integrated. For example, ecological approaches can help identify what types of feedback processes might yield negative unintended consequences (biotype evolution, alteration of ecosystem processes, gene escape). But in many cases possible remedies to these concerns can be substantially improved by molecular methods (plant sterility, localized expression, exogenously triggered expression, etc.).

Some immediate suggestions for improving the environmental safety of genetically engineered trees include:

1. Limit deployment to plantation trees, as opposed to suggestions (not made at this meeting) of using insect vectors or other means for naturally regenerated trees.

2. Limit deployment to sterile trees, and conditions under which spread of vegetative material can be prevented.

3. Employ biotype prevention tactics when pest resistance genes are employed.

4. Employ risk assessment procedures used to evaluate planned releases of biological control agents as a template.

5. Recognize that short-term risk assessment programs favored by current funding approaches bias our understanding in a direction that underestimates ecological risk.

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Forest Biotechnology Perspective

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Based on plenary lectures and discussions, we believe there was strong support from most meeting participants for the following conclusions:

1. Increasing human demand for wood and fiber will be increasingly met from intensively managed plantation forests. As the Earth's human population grows by 50% (to 9 billion in 2050) and standards of living increase, there will be a commensurate rise in demand for the forest products. This wood and fiber must be produced in a manner that is economically and ecologically sustainable. Plantation forests, intensively managed with the best tools of modern agriculture—irrigation, fertilization, weed control, and genetic improvement—will supply much of the world's wood needs and spare native forests by concentrating wood and fiber production, particularly that for industrial uses, on just 1%–10% of the land area now used for timber harvest. The growing science of genomics—where the structure and function of large numbers of genes are analyzed and compared across species—will provide many new opportunities for the use of genetic engineering to aid in the rapid domestication of trees, including increasing yield and the customization of woody feedstock qualities for various fiber and energy uses.

2. Novel aspects of genetically engineered plantation forests require long-term multidisciplinary field research. Intensive plantation forestry, while making use of many methods derived from agriculture, differs from agriculture in several important ways; the longevity of trees, their lack of domestication, and the frequent proximity of wild relatives are three such differences. There is a great deal of knowledge and experience to be gained from starting "medium-scale" experiments (tens to thousands of hectares) with GM trees in plantation forests. Such field trials would allow issues such as stability of trait expression, tree health, degree of genetic containment, and non-target effects to be monitored on ecologically relevant temporal and spatial scales. Risks and benefits could therefore be quantified. As in many other forest research areas, the paradigm of "adaptive management," where economic and ecological issues are examined during initial stages of use, and adjustments made to management based on results, will be important for GM trees if economic and ecological issues are to be studied adequately.

3. Fertility reduction will be important for many applications. Systems for fertility reduction ("sterility") will be critical for many commercial uses of GM trees, to minimize gene flow into natural ecosystems. Because several options exist for achieving fertility control, mounting an aggressive research program, including long-term field trials with carefully chosen species, genes, and environments, seems warranted. Developing a partnership with ecologists, population geneticists, evolutionary biologists, regulators, companies, and interested environmental NGOs to assist in study design will be necessary and desirable.

4. Domestication traits pose less environmental risk. There are clear biological distinctions among most traits being considered for genetic engineering with respect to risk assessment. Some are clearly domestication traits, in the sense that they may improve productivity within tree farms but are highly likely to enfeeble trees in the face of natural selection (and thus pose no risk of increased invasiveness). Sterility, dwarfism, and lignin modification are examples. Other traits may have benefits in wild populations, or reduce efficiency of human control; examples are insect resistance based on novel toxins, or herbicide resistance, respectively. For situations where significant wild populations are adjacent to plantation forests, gene flow of domestication transgenes pose little ecological concern, and thus do not warrant the same degree of empirical scrutiny as possible fitness- or weediness-related genes. For these genes, uncertainties can likely be resolved via adaptive management (see above).

5. Biological analogy between invasive exotics and transgenics is specious. There was strong consensus that the analogy between invasive introduced organisms and transgenic organisms is of little biological merit. Because of the vast differences in the degree of genetic and ecological novelty between novel species and transgenics with one or a few novel genes, the ecological risk from invasive exotics is much larger and less predictable than for transgenics with well-characterized genes. The well-established methodology for assessing risks of exotics, however, can be useful for helping to guide risk assessments of transgenic trees.

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Environmental NGO Perspective

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Environmentalists hold a great diversity of views about GE trees; we are presenting our personal views, not the “NGO position”. In this context, we note the small number of environmentalist participants in this conference.

The potential role of GE trees is part of a larger discussion about forestry and resource use issues. There are likely to be alternatives to the GE paradigm—alternatives that we urge be explored thoroughly.

This conference represents a small step toward both reaching out to various viewpoints and exploring the wider resource use issues and alternative approaches.

However, the statements this morning indicate that few have absorbed the qualms raised by ecologists speaking here. We hope that people will continue to think about the issues we and others have raised.

MODERATOR PERSPECTIVES

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Lessons from Twenty-five Years of Debate on the Risks and Benefits of Biotechnology

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In the early 1970s it became apparent to the molecular biology community that it was soon going to be possible to put foreign (eukaryotic) genes into viruses or into bacterial plasmids to produce so called “recombinant DNA” molecules. The significance of this feat was that it promised to provide a means to amplify genes from any source of interest (for example, humans) to greatly facilitate the study of gene structure and function. (Prior to this achievement it was virtually impossible to study gene structure in organisms more complex than viruses.) In the early - mid 1970s several laboratories were engaged in a race to succeed in ““gene splicing”” research. Some labs were trying to use fairly complicated chemical splicing approaches to introduce genes into viruses. However, the real breakthrough came with the discovery of restriction endonucleases (restriction enzymes) which made it possible to easily splice genes into bacterial plasmids. The bacterium of choice for this research was *Escherichia. coli* because much was known about the genetics of *E. coli* and its constituent plasmids. Very quickly plasmids of *E.coli* were engineered with antibiotic resistance genes as selectable markers to use in recovering plasmids with novel gene inserts. For example, one of the first such plasmids, pBR322, was constructed to carry resistance for tetracycline (tet) and ampicillin (amp). Thus insertion of a recombinant DNA molecule into the tet gene yielded an *E. coli* colony that was tet sensitive and amp resistant, providing a quick screening method for recombinant plasmids.

The irony was that all of this depended on exploiting years of research on *E. coli, a* bacterium that is a resident of the human gut. So, there was a lot of obvious concern about what risks this might pose for human health. Could recombinant DNA experiments inadvertently produce new pathogenic strains of *E. coli* that might pose a human health risk? Were there potential risks to the environment? Some even raised the question should we be creating entirely novel organisms that were outside the bounds of natural processes? In 1975 a major conference was organized under the auspices of the National Research Council at Asilomar in California. The organizers of that meeting were people like Paul Berg, Maxine Singer and others prominent in the research community. The question addressed by the conference was how to proceed with recombinant DNA research safely. The participants at the Asilomar conference identified measures to minimize risk by (1) focusing on ways to create attenuated strains of *E. coli* which could not live outside the laboratory. (The K12 strain of E. coli was quickly developed for this purpose.) And (2) agreeing on a regulatory framework to govern Federally funded research in the area of recombinant DNA technology. (There was very little private sector recombinant DNA research to be concerned about at that time.)

As a direct consequence of the conference, a process was developed to regulate publicly funded research in recombinant DNA technology so as to prevent research that might pose threats to human health or to the environment. For example, certain kinds of experiments with recombinant DNA in viruses were identified as too risky and it was agreed that these would not be pursued. Most publicly funded recombinant DNA research was supported by the National Institutes of Health (NIH) and so the initial responsibility for organizing a regulatory system fell on NIH. The NIH created the RAC (Recombinant DNA Advisory) Committee to create levels of containment appropriate for different categories of experiments and to review the progress of recombinant DNA research with respect to safety. The RAC committee experience was successful and over the ensuing decade or so, the containment prescriptions which the original RAC committee developed for different kinds of experiments, were progressively relaxed as more was learned about the technology and its associated risks.

For a young scientist like myself, the debate of the 1970s was very stimulating and intellectually exciting to observe, albeit from a distance. The debate raised many important questions about scientific responsibility and about how to anticipate some of the risks and impacts of new technologies, while at the same time allowing research to progress. Relatively quickly recombinant DNA research began to pay off with new approaches to human health. One of the first breakthroughs was the engineering of genes for the production of human insulin, thus assuring a safe and adequate supply of this essential product for diabetics. Many other novel pharmaceutical products have since been developed and these have increased the standard of human health.

Virtually from the start it was clear that recombinant DNA methods and their associated technical innovations might have a large potential impact in agriculture and forestry. Beginning in the mid-late 1980s, the USDA and other organizations began a series of workshops focused on the risks associated with the field testing and commercialization of transgenic crops. I had the opportunity to participate in four such workshops during this period. All of the potential risks associated with the applications of these technologies in agriculture were identified during this process and to my knowledge no new credible risks have been identified in the ensuing decade of discussion. Moreover, the National Research Council produced a series of influential reports on different aspects of the use and deployment of transgenic organisms beginning in the late 1980s and continuing to the present (yet another NRC report on the regulation of transgenic crops is due out in October of 2001). Despite this long history of study and debate, and despite the clear successes of biotechnology in pharmaceutical development, a segment of the public still harbors serious concerns about the impacts of these technologies in food production and in forestry. Somehow we have failed to convince a segment of the public that we can be trusted to manage these new technologies in ways that avoid harm to the environment or to human welfare. In short there appears to be a credibility gap.

In seeking reasons for the persistence of the credibility gap it is instructive to compare some essential differences between the systems of science in biomedicine and in agriculture/forestry. To begin, there is a healthy balance in the biomedical area between public good research investment and private investment, which is markedly different from that in agriculture/forestry. The National Institutes of Health has a research budget of roughly 16 billion dollars a year largely devoted to investments in public good research. In contrast, investments in public good research in agriculture/forestry are an order of magnitude smaller and are dwarfed by private sector research investments in this sector. As a consequence, it may be more difficult for the public to accept that we as scientists are acting in the public good rather than in the interests of private gain because we are more dependent on private investment for our research agenda.

What are some of the other reasons that we are still debating these issues today, 25 years later? Perhaps another reason is that we have a regulatory apparatus for the monitoring and development of transgenic crops and transgenic forestry products that is cumbersome. It is a three-agency agreement that fragments responsibilities and is difficult to understand. It is not transparent and hence it is not clear to the public that the regulatory system necessarily acts in the public interest. Finally, there is the big question that has come up repeatedly in this meeting, who benefits and who bears the risk? It is clear to all of us that we individually benefit from research in biomedicine; our lives have been extended, the range of diseases that pose threats to us and to our families has been diminished. We are generally a more healthy society today than we were a quarter century ago. Whereas it is not clear in the agriculture/forestry sector that we individually benefit from the research agenda. We have done a poor job of convincing the public that they will benefit from a wider range of useful products based on biotechnological innovation in the future. The challenge for the future is to address this fundamental question of public benefit.

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The Urgent Need for Field and Laboratory Science to Inform Ethical and Policy Debates

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There is much that could be covered in a summary of this conference; I may miss some things that strike you as vital. But these are some points that resonated with me. I found four take-home points. I think these points could become what I call barrier busters, things needed to help us move to the next level of understanding.

Take-home point No. 1: *We need field research.* We cannot get the next level of much-needed data on genetically modified organisms without empirical research, such as field trials, which must be long term and comprehensive. As several have pointed out at the conference, we thus far have very little data on field performance and safety. Thus, our discussions of the prospects for both benefits and risks are loaded with speculations based on concepts and lab work, too much speculation and not enough articulation as testable hypotheses. At a minimum, we need to begin recasting our speculations so they become testable hypotheses and then describe what we believe would be the evidence that would refute these hypotheses. We must take this fundamental step in the scientific method in order to move beyond a discourse of speculations based on concepts and theories and ideologies. When we do conduct the research, we must show people the data and use the data to continue the discussions.

Take-home point No. 2: *We need to question the universal appropriateness of the precautionary principle.* We heard mention a number of times in the concluding presentations of the precautionary principle; if we do not know all the ramifications of something we should be very cautious in how we proceed. This is not the only option for public policy, though it is certainly an appropriate consideration. Many of the advances in our civilization have come from the opposite of a preoccupation with caution; they have resulted from a bias for boldness. Society must always ask questions such as, in what ways and under what conditions will we use biotechnology and genetically modified trees? At what point do we determine that our knowledge is sufficient, the risks acceptable, and the benefits equitable, such that we should proceed with field use of these organisms? At the same time, however, we face enormous natural resource challenges: how to equitably feed, clothe, and house current and future generations while simultaneously taking care of environmental health. While some will argue that we must wait until all potential outcomes of the potential roles for new technologies are perfectly certain, others must step forward to tackle these challenges boldly, to go where others have never been or are too timid to venture. We need a judicious balance between our tendency for caution and a bias for boldness. Perhaps it is time for the scientific community to open up the precautionary principle to some critical thinking about whether it is in fact the most prudent public policy in all natural resources issues ? does it serve well a dynamic world that is growing in numbers of people, many of whom are living under great inequities in a world that continues to be full of surprises?

Take-home point No. 3: *When do we go public? Is this the right time for public dialog on GMOs?* I raise this issue because I'm not sure from the dialog that we have had this week and from all the other issues that people are talking about in the natural resources policy arena whether the time is really right for a visible, open public dialog on genetically modified organisms. This dialog is certainly appropriate eventually, but if we decide to move now into the public policy arena, then what are the message we are going to use to entice people to engage in a meaningful and constructive dialog? Who will carry the messages, how should we structure the dialog, what do we expect the outcomes to be? And what sort of grand visions do we use to stimulate people within that dialog? Maybe the time is right, but I would much prefer that we be at least to the stage of having testable hypotheses and proposed research trials rather than lots of speculations before opening the dialog. Whenever we open the public dialog, we need to be abundantly open and transparent about our assumptions and our unknowns.

Take-home point No. 4: *Clarify the role of science in policy.* We must get a better grasp of the appropriate roll for science in what is inherently a socio-political process, that is the public policy process. Science informs policy choices; it tells us what's going on, what's possible, and what the likely consequences of choices might be. It does not and should not tell us what the choices should be, though individual scientists certainly will have opinions on that. Science leadership does not mean that scientists make the decisions all by themselves; the political process and the markets make the choices. We are, as Dr. Paul Risser said in his opening comments at this conference, at the intersection of many issues relevant to one of the most vital ecosystems for life: forests. Scientists cannot drive or decide the choices that people make about forests. On the other hand, we cannot have rational and prudent choices without science being a key player. So we must create complimentary roles for science and the policy process. Toward that end, I am intrigued by what Sue Mayer described as 'multi-criteria mapping'. This may be the framework for getting scientific perspectives into the social and political discussion arena.

These are main points that I take home from this conference. If we take them on, then maybe they could serve as the bridges to the next levels of understanding on the legitimate roles for GMOs in our future forests. But one final thought: I am really intrigued by what Dr. David Victor talked about, this idea of a great forest restoration. Worldwide, we are restoring forests while we preserve some and manage others to sustain desired conditions of environments, economies, and communities. So far we are doing this with existing and somewhat traditional technologies. Not all nations are on track with this restoration and are still losing forested area. Are genetically modified organisms essential to make this great forest restoration work, or are they still down the road somewhere, or do they fit at all? I think those are legitimate questions for all of us to consider as we leave this conference.

APPENDICES

Proceedings of the First International Symposium on
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S.H. Strauss and H.D. Bradshaw, eds. College of Forestry,
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www.fsl.orst.edu/tgerc/iufro2001/eprocd.pdf

Appendix 1 — Exit Survey of "EcoSocial" Symposium Participants

TABLE 1. SUMMARY OF SURVEY RESPONSES (N=136).

Survey questions	Responses (%)			
	Agree	Neutral	Disagree	No response
1. Intensively managed plantation forests (including hybrids and exotic species) can make a significant contribution to environmental quality and sustainable production of wood and fiber for human use.	91	6	3	0
2. Sustainably harvested natural forests are not sufficient to meet global wood demands in the next half century.	76	15	9	1
3. The specific traits of plantation forests, and not the method by which the traits were produced (conventional breeding or GM), are the primary determinants of the risks and benefits of deployment.	77	14	9	1
4. GM of plantation forests is unethical, regardless of any scientific consensus on risks and benefits.	1	4	94	0
5. There should be a moratorium on any field research with GM trees, even if reproduction is prevented.	8	7	85	0
6. The current US regulatory framework for GM trees is adequate to insure environmental safety and enable socially acceptable technical progress.	24	53	24	1
7. The dominating roles of patents and corporations in GM research and application are major barriers to public acceptance.	54	26	20	0
8. The ecological issues that GM plantations present are different in detail, but not in magnitude, from those common to intensive plantation systems.	72	13	16	1
9. Experiments on a large scale (plantation to landscape level) and long time frame (at least equal to the age at harvest) are required for learning about the realistic levels of risks and benefits of GM trees.	64	14	21	0
10. No amount of research, or containment methods, can reduce the ecological risks of GM plantations to an acceptably low level.	10	4	86	0
11. The ecological risks of GM trees should be assessed only by scientists with no financial ties to industry or activist organizations.	37	16	47	1
12. GM trees are a threat to biodiversity at all spatial scales.	11	11	78	0
13. The risks for invasiveness from GM trees can be predicted well from the nature of the traits imposed.	36	33	31	0
14. Traits that move qualitative aspects of trees out of the range produced by natural selection will tend to domesticate, and thus can be assumed to be of little concern for increasing invasiveness of GM trees or progeny (e.g., short stature, modified wood, non-flowering).	40	40	21	0
15. Fertility reduction systems are needed to minimize spread of all types of GM trees.	58	11	31	0
16. Single, exogenous genes for pest resistance, such as Bt, pose significant risks for ecological damage.	27	26	46	0
17. Single or multiple sterility transgenes, used with the best available transformation, gene expression-stabilizing, and field screening methods, can provide adequate fertility reduction for commercial uses of GM trees.	63	28	9	0
18. The analogy between GM and intentionally introduced, but invasive and ecologically damaging exotic species, is an ***in***appropriate one, considering the magnitude and uncertainty of their biological risks.	59	23	18	1
19. GM trees pose a significant threat to wild forests through their increased invasiveness.	7	15	78	0

(Table 1. continued)

Survey questions	Responses (%)			
	Agree	Neutral	Disagree	No response
20. GM trees with modified wood pose much greater concerns than trees whose wood has been modified via conventional breeding (after both have performed favorably in half-rotation field trials).	15	15	70	0
21. Sufficient basic and applied research upon the genetic stability and ecosystem behavior of GM trees, and upon the design of biological safety mechanisms, can create environmentally safe and societally beneficial trees and outcomes.	88	8	4	0
22. I am actively involved in research that is expected to facilitate some commercial uses of genetically modified trees within a decade.	62	6	32	1
	Yes		No	
23. I am a molecular biologist or forest biotechnologist.	78		22	
24. I am a college student.	24		76	
25. I have a Ph.D.	79		20	
26. The conference was informative.	96		2	
27. The conference focused on the important issues.	93		4	
28. The lectures were well delivered and valuable.	93		3	
29. The conference was well organized.	97		1	

TABLE 2. DETAILED SURVEY RESPONSES.

Survey questions	Responses (%)					
	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	No response
1. Intensively managed plantation forests (including hybrids and exotic species) can make a significant contribution to environmental quality and sustainable production of wood and fiber for human use.	54	37	6	2	1	0
2. Sustainably harvested natural forests are not sufficient to meet global wood demands in the next half century.	44	32	15	7	2	1
3. The specific traits of plantation forests, and not the method by which the traits were produced (conventional breeding or GM), are the primary determinants of the risks and benefits of deployment.	52	25	14	7	1	1
4. GM of plantation forests is unethical, regardless of any scientific consensus on risks and benefits.	0	1	4	26	68	0
5. There should be a moratorium on any field research with GM trees, even if reproduction is prevented.	3	5	7	22	63	0
6. The current US regulatory framework for GM trees is adequate to insure environmental safety and enable socially acceptable technical progress.	4	19	53	20	4	1
7. The dominating roles of patents and corporations in GM research and application are major barriers to public acceptance.	13	41	26	18	2	0

(Table 2. continued)

Survey questions	Responses (%)					
	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	No response
8. The ecological issues that GM plantations present are different in detail, but not in magnitude, from those common to intensive plantation systems.	19	53	13	13	3	1
9. Experiments on a large scale (plantation to landscape level) and long time frame (at least equal to the age at harvest) are required for learning about the realistic levels of risks and benefits of GM trees.	27	37	14	17	4	0
10. No amount of research, or containment methods, can reduce the ecological risks of GM plantations to an acceptably low level.	2	8	4	29	57	0
11. The ecological risks of GM trees should be assessed only by scientists with no financial ties to industry or activist organizations.	12	25	16	33	14	1
12. GM trees are a threat to biodiversity at all spatial scales.	4	7	11	30	48	0
13. The risks for invasiveness from GM trees can be predicted well from the nature of the traits imposed.	5	31	33	25	6	0
14. Traits that move qualitative aspects of trees out of the range produced by natural selection will tend to domesticate, and thus can be assumed to be of little concern for increasing invasiveness of GM trees or progeny (e.g., short stature, modified wood, non-flowering).	4	36	40	18	3	0
15. Fertility reduction systems are needed to minimize spread of all types of GM trees.	25	33	11	25	6	0
16. Single, exogenous genes for pest resistance, such as Bt, pose significant risks for ecological damage.	6	21	26	35	11	0
17. Single or multiple sterility transgenes, used with the best available transformation, gene expression-stabilizing, and field screening methods, can provide adequate fertility reduction for commercial uses of GM trees.	14	49	28	7	2	0
18. The analogy between GM and intentionally introduced, but invasive and ecologically damaging exotic species, is an ***in***appropriate one, considering the magnitude and uncertainty of their biological risks.	19	40	23	11	7	1
19. GM trees pose a significant threat to wild forests through their increased invasiveness.	1	6	15	44	34	0
20. GM trees with modified wood pose much greater concerns than trees whose wood has been modified via conventional breeding (after both have performed favorably in half-rotation field trials).	5	10	15	35	36	0
21. Sufficient basic and applied research upon the genetic stability and ecosystem behavior of GM trees, and upon the design of biological safety mechanisms, can create environmentally safe and societally beneficial trees and outcomes.	43	45	8	2	2	0
22. I am actively involved in research that is expected to facilitate some commercial uses of genetically modified trees within a decade.	31	31	6	11	21	1
23. I am a molecular biologist or forest biotechnologist.	57	21	0	5	17	1
24. I am a college student.	3	21	0	11	65	10
25. I have a Ph.D.	69	10	1	5	16	3
26. The conference was informative.	66	30	1	1	1	1
27. The conference focused on the important issues.	53	40	3	1	2	0
28. The lectures were well delivered and valuable.	45	48	4	2	1	0
29. The conference was well organized.	68	29	1	0	1	0

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