Forest Productivity:

Producing Goods and Services for People

Thomas R. Crow, Daniel C. Dey and Don Riemenschneider

This report is dedicated to David S. Shriner (1945-2003), who as Supervisory Assistant Director of the Forest Productivity Integrated Research and Development Program provided a sustaining leadership and an endearing enthusiasm for landscape change research at the North Central Research Station.

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Forest Productivity: Producing Goods and Services for People

A Progress Report

North Central Research Station
Forest Productivity Integrated Research and Development Program

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Science Co-Leaders

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Executive Summary

In 1999, the North Central Research Station (NCRS) created three integrated research and development programs to deliver policy-relevant research to clients. The mission of one of these, the Forest Productivity Integrated Research and Development Program, is to develop the scientific knowledge and tools needed to increase and maintain forest productivity and the supply of forest products in the Midwest region, and to do so using sustainable silvicultural systems that are socially acceptable, economically viable, and ecologically feasible. This document is a progress report to stakeholders of the Forest Products Integrated Research and Development Program, highlighting the results from 1999 to 2003 that addresses key issues in the Midwest region.

How productive are our forests? Based on a recent assessment of the status of timber resources, forests in the Midwest are producing timber much faster than they are losing it to mortality and land conversion, or to harvest for wood and paper products. In the past 50 years, the volume of timber has doubled in the region. However, people are consuming far more wood than we are currently growing, harvesting, and processing in the region. The challenge then is to learn how to sustainably manage the timber resources to meet the needs for wood and fiber in our region in a socially and environmentally responsible manner. NCRS scientists have developed productivity models and maps based on climate and site conditions to help managers decide where to invest in aspen management to produce raw material for the Lake States pulp and paper industry. The NCRS also conducts annual forest resource inventories and provides summaries of productivity and other forest conditions to help planners, economic developers, managers, and researchers better understand current forest conditions, determine changes in forest lands due to population growth and rural development, and project future forest conditions.

How productive can our forests be? Overall, the region's forests are not growing at their full capacity because of a lack of investment in more intensive forest management and plantation production and a general failure on the part of forest landowners to use good forestry practices or to have forest management plans. Potential forest productivity can be increased by improving the biological growth potential of individual trees. Improved seedlings can be used to supplement the natural regeneration of forests or to establish intensively managed plantations. Advances in tree improvement and the intensive culture of cottonwood, hybrid poplar, black walnut, and oaks have been made by NCRS scientists. They are evaluating the genetic control of and role in tree survival, growth, wood and fiber quality, nut quality, resistance to insect and disease agents, and tolerance of chemicals such as herbicides and pollution. Planting high quality seedlings in intensively managed plantings is one way to increase the productive potential of our forests. Scientists at the NCRS also are evaluating ways to increase the growth and yield potential of native forests. For example, commercially thinning young aspen stands may increase their productive capacity by managing competition and harvesting what would normally be lost to natural mortality. Other NCRS scientists are looking into the usefulness of forestry cooperatives among private forest owners, who hold the bulk of midwestern forests. Cooperatives may lead to increased forest productivity on nonindustrial private lands by promoting education on good forest management, increasing landowner awareness of how timber production can be compatible with their other objectives, and facilitating the harvest and marketing of timber.

What limits forest productivity? Forest productivity is affected by numerous important ecological, environmental, and social factors. Several prominent non-native, invasive species are threatening the health and productivity of our forests. The gypsy moth, introduced into the U.S. late in the 19th century, has moved into the Lake States region and will likely cause extensive forest mortality. Recently, the emerald ash borer entered the Midwest region from China and is now decimating ash trees as it spreads from southern Michigan. NCRS scientists are providing basic information on the biology and ecology of exotic forest insects to support control measures. Scientists also are developing management systems to make forests more resilient to attacks by native insect pests and disease and environmental stresses from drought and pollution that cause catastrophic forest declines much like the current massive oak die-off taking place in the Ozark Highlands. NCRS scientists studying climate, pollution, and forests are developing a better understanding of the effects of rising levels of ozone and carbon dioxide on forest growth and mortality, and they are modeling large-scale patterns of pollution across the Midwest region. Other scientists are assessing how timber market values change private landowners interests in and willingness to practice forest management on their properties. Urban sprawl and housing development in rural areas cause losses of forests or reductions in amounts of forests that are managed. Urban and recreational development of forests is widespread throughout the Midwest region with unknown consequences on forest productivity. We are evaluating housing development effects on fragmentation of forests in the Lake States and assessing the implications changing ownership has for timber availability.

How do we enhance forest productivity? One strategy for increasing forest productivity is to intensively manage plantations of short rotation hybrid poplars and cottonwoods for fiber, and fine quality hardwoods such as black walnut, black cherry, and oaks for high value veneer and saw logs. NCRS scientists have developed genetically improved seedlings and the cultural systems needed to grow trees in plantations. Their tree breeding programs have identified more productive varieties, while advances in cloning and genetic modification technologies are needed to improve wood character and value. They developed seedling quality standards for the tree nursery industry and produced practical guidelines for managing competing vegetation, as well as insects and diseases in socially and environmentally acceptable ways. Forest productivity also can be increased by practicing silviculture and implementing best management practices in native forests. Forest management can increase tree growth and wood quality and value, improve forest health, and lower losses to mortality. Even small gains in productivity resulting from better management are substantial when they are realized on the 73 million acres of timberland in the Midwest region. The NCRS has a long history of developing methods for managing hardwood and conifer forests more productively. Best forestry practices and management recommendations have been documented in numerous NCRS handbooks for managers and most recently in a landmark book on managing oak forests. NCRS scientists are evaluating methods for reforesting marginal agricultural bottomlands, and they are producing guidelines for managing forests and plantations on these high quality areas, which increases productivity by adding to the forested acreage in the region. Results of the NCRS' long-term soil productivity research, part of a nationwide program, will guide forest management to control adverse effects on long-term soil productivity.

The Forest Productivity Integrated Research and Development Program at the North Central Research Station is contributing knowledge needed to manage our forests more productively and to help make decisions about using the region's forests in an era of growing population, increasing consumption of forest products, and rapid urbanization of forest lands.

FOREST PRODUCTIVITY: PRODUCING GOODS AND SERVICES FOR PEOPLE

A PROGRESS REPORT

INTRODUCTION

American forests make vital contributions to our well-being at many levels—from the local community, to the region, the Nation, and even the global community. The economy of the Midwest region, for example, depends heavily on the supply of wood as an industrial raw material, and the forests in the region provide many benefits—wildlife habitat, recreational opportunities, clean water, and spiritual values—to name just a few. In short, forests affect our lives in many important ways.

But there are concerns about sustaining healthy forests and all they provide. Although fire is seen as one of the greatest risks, other factors, including pests and pathogens (especially invasive species), global change, soil compaction, forest fragmentation, and exploitative harvesting all affect forest health. Regardless of what is causing the decline, forest productivity is a key integrator of ecosystem health.

Here are a few reasons why we are concerned about forest productivity, forest health, and forest sustainability.

- Global demand for wood and other forest products is increasing at twice the rate of population growth.
- Changes in land use patterns and social preferences mean that fewer acres in the regional, national, and global woodbasket are available for harvesting.
- Introduced insects and disease agents are reducing the vigor of the forest over large areas, e.g., the gypsy moth.
- In the United States, we are not harvesting as much wood as people are consuming.
- The productivity, health, and sustainability of the forest are inextricably linked with human welfare.

Given these concerns, we are exploring the gap between the actual and potential growth of the regional forest, identifying the reasons for the gap, and considering how our research is providing opportunities for closing this gap.

We define forest productivity in terms of traditional forest products where productivity is measured as the annual average change in cubic feet, board feet, cords, or biomass of wood. Losses in volume to tree mortality and harvesting are also measured and subtracted from growth to provide net growth. Although we are interested in the amount of wood produced in a given time, we are especially interested in the quality of the wood (fig. 1). High quality wood is free of defect and meets the highest standards for industrial raw materials. High quality generally equates to high value. There is a great but largely unrealized potential for growing high value wood in the forests of the Midwest region.

Forests in the Upper Midwest are both extensive in their distribution and varied in their composition (Shifley and Sullivan 2002). Thirty percent of the seven-State Midwest region is forested. In the Central States of Iowa, Indiana, Illinois, and Missouri, forests cover nearly 23 million acres, while in the Lakes States of Michigan, Wisconsin, and Minnesota, forest land accounts for more than

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Figure 1.—*A northern hardwood forest of mixed sizes and ages dominated by sugar maple located on the Ottawa National Forest in upper Michigan. High value is gained in these forests by managing for high quality wood.*

47 million acres. Ninety-five percent of this forest land is classified as timberland—that is, land sufficiently productive to grow commercial trees and where timber harvesting is not restricted by legislation or administrative action.

Existing forests are the result of past uses and, in some cases, past abuses. In the Midwest region, most of the forests were heavily and repeatedly harvested during the late 1800s and early 1900s (Stearns 1997, Whitney 1994). Wildfires were common until the 1930s when organized fire suppression was begun. Many cutover forest lands were farmed and subsequently abandoned to return to forest cover. Lack of forest management, logging by high grading (i.e., repeatedly taking the best and leaving the rest), and wildfires and grazing have created forests that are far below their potential in quality and quantity of wood grown. In fact, Missouri leads the Nation in the proportion of live timber that is cull (Spencer and Kingsley 1991). Today, forests in the Central States are mature, densely stocked with trees, and dominated by relatively few species. These conditions can potentially lead to staggering losses in forest productivity because of insect and disease outbreaks, invasion of exotic pests, and environmental stress such as drought and pollution.

Present forests in the Midwest region are very different from those just 70 or 80 years ago (fig. 2). The change represents a remarkable recovery from extensive harvesting and fire that occurred in the late 1800s and early 1900s, starting first in Michigan and working westward across the northern Lake States then south to Indiana, Illinois, and Missouri. In the Lake States, faster growing species such as aspen, birch, and jack pine regenerated following disturbance, and they are now being replaced in many locations by slower growing species such as sugar maple (Schulte and Crow 2003). In the Ozarks, mixed oak-pine forests were converted to oak forests, reducing biodiversity and leaving them vulnerable to drought and insect damage as they reach maturity. On many of the most productive sites in the Central States, mixed oak forests have been replaced by sugar maple, resulting in declines in wildlife habitat quality, species diversity, and economic potential. Over the past century, the seedling and sapling forests that regenerated in the Midwest region have matured, and sawtimber is now the dominant size class. At present, timber growth exceeds timber harvest, and the region's forests have the potential to be highly productive—more so than at any time in the past 80 years. At the same time, the region's forests supply relatively little of the Nation's demand for forest products; face threats from insects, disease, fire, and drought; and are under increasing pressure to meet the recreational and aesthetics expectations of the 47 million people who live here.

Increasing forest productivity is the primary goal of our research. However, such increases must maintain ecological diversity and be sustainable. Our research integrates a broad spectrum of concerns from individual organisms to forest communities to landscapes that contain a mix of forests, urban areas, and agricultural lands. The matrix in table 1 illustrates an organizing framework for this research. For example, there is interest in moving from management of single species and single age classes in natural forests to management strategies that use mixed species and multiple age classes (Palik and Zasada 2003). This research falls within Intermediate Management Intensity in table 1 and at the Stand and Landscapes scales, i.e., cells v and iii. In another study, Gustafson (1996) explored the possibility of clustering timber harvesting in both time and space to reduce forest fragmentation. This study applies to Extensive Management on the Landscape, cell vi, in table 1. Studies referenced in our report will be located within this matrix.

Our report summarizes important issues related to forest productivity in the region and brings readers up to date on research progress since the Forest Productivity Integrated Program was initiated in 2000. Progress and results of new studies funded through the integrated program as well as new and ongoing long-term studies are reported. It is often difficult to distinguish between the two sources of funding—just as it should be with an integrated program of research.

Figure 2.—*A mature stand of jack pine located in the Superior National Forest in northeastern Minnesota. Jack pine, a fire-dependent species, is in decline throughout the Lake States region due to the suppression of fire.*

Table 1.—*A model for evaluating Research and Development (R&D) priorities and direction in the Forest Productivity Integrated Research and Development Program. Examples of R&D activities are provided within the matrix as defined by management intensity and scale of application.*

	Management Intensity		
Scale	**Extensive**	**Intermediate**	**Intensive**
Landscape	(vi) How does forest management change the landscape character? How does a managed landscape differ from one formed by natural disturbances?	(v) How does the mix in land ownership and diversity of land owner management objectives affect regional wood production?	(iv) How and where within the landscape should new technologies for intensive culture be deployed? Which sites within the landscape are best suited for intensive culture?
Stand		(iii) What incentives and/or organizational structures (e.g., landowner cooperatives) promote increased forest productivity?	(ii) What improvements in vegetation management, mid-rotation silviculture, forest establishment are required?
Organism			(i) How can molecular biology and biotechnology be used to increase forest productivity? What are the biological limits to growth? How should technology be deployed?

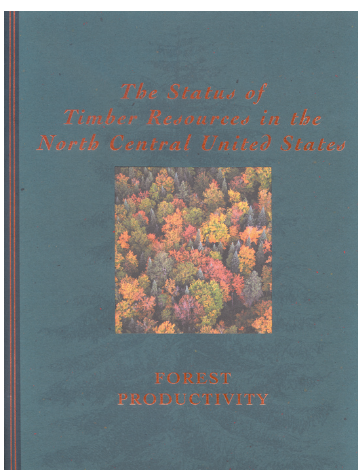
How Productive Are Our Forests?

Current Status

The forests in the Midwest region are not as productive as they could be because of their present composition, past mismanagement, current lack of management, climate, and soils. This is reflected in the fact that the Upper Midwest has 14 percent of the Nation's timberland but grows only 10 percent of the Nation's wood (Shifley and Sullivan 2002). The reasons for this difference suggest some of the opportunities we have for increasing productivity. Just five species—aspen, sugar maple, red maple, red oak, and paper birch—account for half of the timber volume in the Lake States. Although the Central States have more tree species compared to the Lake States, the dominants tend to be various species of oak and hickory. Many of these species have the potential to develop high commercial value.

Assessing Current Forest Productivity

The report *The Status of Timber Resources in the North Central United States,* authored by Steve Shifley and Neal Sullivan, is a good source of information about the forest area, ownership, growth, harvest, and consumption of wood within the north central United States (including Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, and Wisconsin).



Copies of the report can be downloaded or ordered at http://www.ncrs.fs.fed.us/, or by writing to the North Central Research Station, 1992 Folwell Avenue, St. Paul, MN 55108 Attn: Publications.

Forest Inventory and Analysis

Working in partnership with State agencies, scientists in the Forest Inventory and Analysis unit at the North Central Research Station collect, analyze, and compile forest resource data for Michigan, Wisconsin, Minnesota, South Dakota, North Dakota, Nebraska, Kansas, Iowa, Missouri, Illinois, and Indiana.

Inventory information for individual States and the entire U.S. is available in a wide variety of printed publications and also available online. Moreover, it is easy to directly access the inventory data via the World Wide Web and create a virtually limitless array of reports and maps based on the latest (or prior) inventory data.

Accessing Forest Data for Analysis

Now you can get the Forest Inventory and Analysis publications for all 11 Midwestern States on one CD that is packed with over 50 years of research.

You can tap directly into the inventory databases on the Web and create your own reports by using the FIA Mapmaker at
http://www.ncrs.fs.fed.us/4801/FIADB/index.htm.
http://www.ncrs.fs.fed.us/4801/hot-topics/mapmaker-ver17/default.asp

Or, you can download inventory reports (or other research publications at http://www.ncrs.fs.fed.us. Follow the link to Publications and Products.

Predicting the Productivity of Aspen

Aspen forests are important to the pulp and paper industry in the Midwest region, and young aspen forests provide critical habitat for wildlife such as the ruffed grouse. Industry and public forest managers and planners need tools to help them sustainably and efficiently manage the aspen resource. Eric Gustafson at the North Central Research Station in Rhinelander, Wisconsin, has developed models that allow managers to predict the productivity of aspen based on site characteristics (soil and topography) and climatic factors (rainfall, temperature, and climatic moisture deficit).

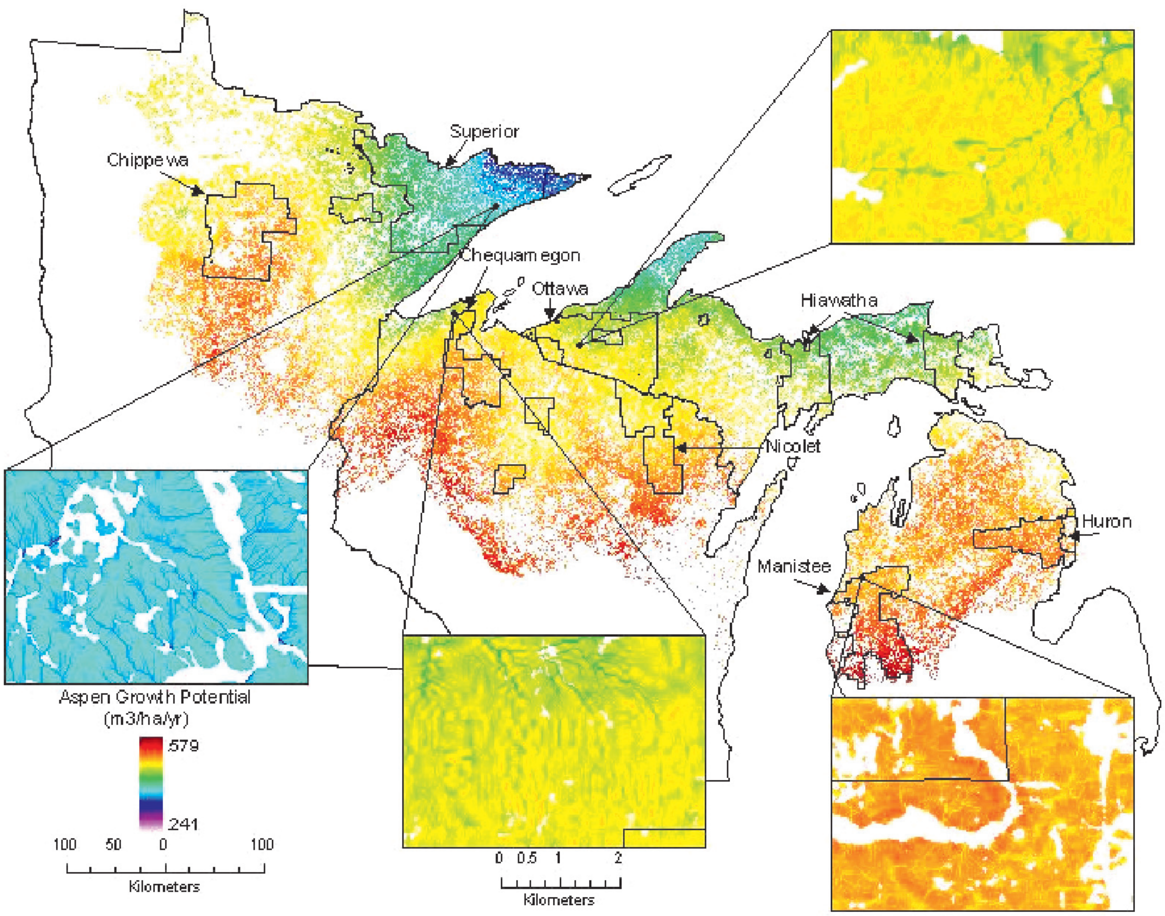


Figure 3.—*The potential for growing aspen in the Great Lakes region. The boundaries of the national forests are delineated.*

Forest managers can use the information in these models to predict and map the potential for aspen growth across the northern Lake States (fig. 3, on previous page). Thus, managers can identify sites that are highly productive for aspen but that currently have few or no aspen trees. This tool helps managers decide where to invest so they can maximize aspen production in an economically efficient manner. This study corresponds to the Landscape Scale and Extensive or Intermediate Management cells (v and vi) in table 1.

Gustafson found that the best sites for growing aspen had higher growth potential than those sites that are currently growing aspen (fig. 4, below). This shows there is a great opportunity to increase forest productivity by simply doing a better job of matching species to the sites where they grow, now that we know how to efficiently identify those sites.

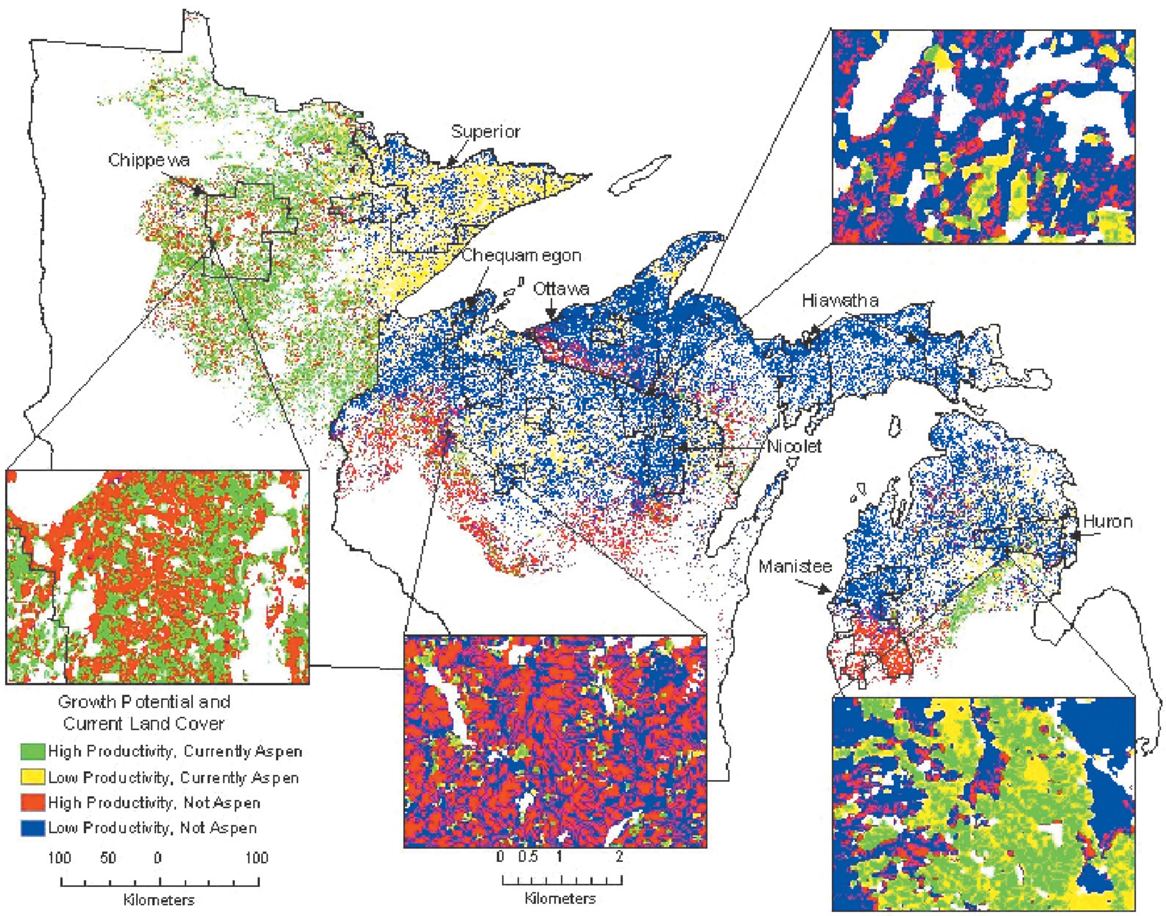


Figure 4.—The current location of aspen relative to sites with the highest growth potential. The boundaries of the national forests are outlined.

How Productive Can Our Forests Be?

Assessing Potential Forest Productivity

There are many reasons why the forests in the Midwest region are not as productive as they could be. It is the physical environment—climate, moisture, soil, physiography—that ultimately determines potential productivity. Compared to the South, the Upper Midwest has a colder climate with a shorter growing season, which translates into lower productivity in the Upper Midwest forests compared to those in the South. Even within a region, there are significant differences in growth potential. On average, forests in Michigan are more productive than forests in Minnesota, and likewise, forests in southern Indiana on average are more productive than forests in northern Michigan.

In spite of the many factors that limit forest productivity (see What Limits Productivity?, page 11), the failure to realize potential productivity in the forests of our region is due primarily to a lack of investment in intensive plantation culture and a general lack of prescriptive silviculture, particularly competition control and commercial thinning, on less intensively managed lands. Most of the other factors limiting productivity we summarize are secondary to these two factors. If we did these two things—**(1) invest more in intensive plantation culture** and **(2) apply existing silviculture tools to many more acres of natural forests**—the other concerns become less important. But there are still basic questions about where to invest and which of the many cultural alternatives will meet the managers' objectives.

We are working to understand more about options and tradeoffs among alternatives for increasing productivity. At the landscape scale, the United States has been classified into broad ecological regions that are similar in climate, geology, and soils (McNab and Avers 1994). Now we are investigating how those regions differ in current forest cover, productivity of existing native forests, forest ownership patterns, pressures related to population density, and potential to increase forest productivity through more intensive management. At a finer spatial scale, we are developing information to guide forest managers in choosing among alternatives for their ownerships. In the long term, intensively managed plantations generally have the capacity to produce more wood per acre than intensively managed natural forests. Likewise, when other factors are equal, intensively managed natural forests will generally produce more wood than extensively managed natural forests or unmanaged forests.

We are investigating how ecological regions differ in current forest cover, productivity of existing native forests, forest ownership patterns, pressures related to population density, and potential to increase forest productivity through more intensive management.

However, increased management intensity generally also requires a greater investment of time and money. We are working to develop better comparisons of the productive potential and investment associated for various intensities of forest management. At the molecular level, we are using genetics to improve the growth, pest resistance, and chemical resistance of trees used in the most intensively managed production systems.

Increasing Aspen Productivity Through Thinning

Aspen management and research have a long history in the northern Lake States because of the importance of aspen to the pulp and paper industry. However, most aspen silviculture research addresses the direct and indirect effects of clearcutting on regeneration. Commercial thinning has not been a significant part of aspen silviculture, but it could increase productivity, especially in young aspen stands as mortality begins to increase due to increasing competition among aspen stems. Through well-planned thinning, it may be possible not only to harvest trees that would otherwise die from overcrowding but also to promote increased growth on the remaining trees and improve wood quality. We are currently testing these hypotheses through a cooperative study among the North Central Research Station, the Blandin Paper Company, the Chippewa National Forest, and the Minnesota Department of Natural Resources.

Role of Forestry Cooperatives in Increasing Forest Productivity

Eighty-five percent of the timberland in the Eastern United States is privately owned, primarily by individuals rather than corporations. There are nearly 10 million such owners in the East, with 59 percent owning less than 10 acres. Increasing forest productivity on the Nation's nonindustrial private forest lands involves many challenges. **One challenge is to convince landowners that wood production complements or even advances other landowner objectives such as creating wildlife habitat or recreation opportunities.** Other obstacles include lack of information, distrust of professional foresters, small parcels that make management uneconomical, and lack of time and money.

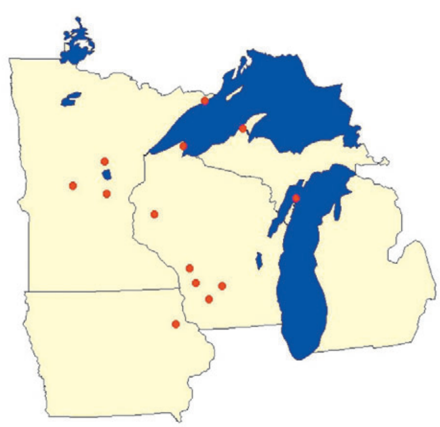


Figure 5.—*Location of current cooperatives in the Lake States.*

Forest landowner cooperatives offer a means for overcoming some of these obstacles. Although landowner cooperatives are not a new idea, only two cooperatives were actively operating in the United States before 1998. More recently, there has been a resurgence in forming cooperatives, much of which has been centered in the Upper Midwest (fig. 5). The new cooperatives, like those in the past, provide members with greater bargaining power, better access to markets, help formulating and implementing management plans, market information, and opportunities to add value to products by working with other landowners in producing and marketing forest products. These new cooperatives also promote forest certification, land protection, and ecological restoration.

What Limits Forest Productivity?

Emerald Ash Borer and Other Unwelcome Visitors

Diseases and insects kill trees and thus decrease forest productivity. Death of individual trees is a normal part of forest development, but when forest health declines precipitously due to abnormal problems with insects and disease, the loss to forest productivity can be significant. Many of the most serious problems are related to non-native (introduced or exotic) diseases and insects.

One such exotic forest pest is the emerald ash borer recently discovered in southeastern Michigan and in southern Ontario, Canada. A native of China, the emerald ash borer probably reached the United States in wooden pallets. Since its arrival, 31 million ash trees growing in southern Michigan have been infected and will die. Death is caused when the ash borer larvae feed on the inner bark (phloem) and girdle the stem. The North American ash resource is at risk from the emerald ash borer.

Emerald Ash Borer

North Central Research Station entomologists working in East Lansing, Michigan, provide basic information on the biology and ecology of exotic forest insects so managers and policymakers can formulate proper strategies. Over the years our work has influenced development of policy and regulations to control various pests on regional, national, and international scales. We are currently helping combat an outbreak of the emerald ash borer, a new exotic pest to North America.

Issue

The emerald ash borer, *Agrilus planipennis,* was discovered infesting and killing thousands of ash trees (*Fraxinus* spp.) in a five-county region of southeastern Michigan in July 2002. A sixth Michigan county was added in September 2002. Evidence suggests that *A. planipennis* first entered Michigan at least 5 years ago. Surveys to determine the full extent of the infested area are underway.

Potential impact

In Michigan, this borer has been observed only on ash trees. It has killed green ash (*F. pennsylvanica*), white ash (*F. americana*), and black ash (*F. nigra*). The trees die when burrowing larvae girdle the water and nutrient conducting tissues along the main trunk. Many trees seem to lose about 30 to 50 percent of the canopy after the first year of attack, and the entire tree is often killed after 2-3 years of infestation. Stress likely contributes to vulnerability. However, relatively vigorous trees also have been killed.

Emerald ash borer is causing the death of highly valuable ash trees in urban areas.

Ash occurs extensively in the natural and urban forests of the Eastern United States. In 2001, it accounted for more than 149 million cubic feet of timber products nationwide. Ash is planted extensively in cities and towns as a hardy urban shade tree. A quarantine restricts movement of ash logs, lumber, firewood, and nursery stock.

Many other introduced forest pests are of concern to forest managers in the Upper Midwest. Gypsy moth, an introduced insect that defoliates both hardwood and conifer trees, especially those found in the oak-hickory forest type, is moving westward and threatens forests in the Midwest (Gottschalk 1991). As the insect expands its range, the first-time infestations result in significant mortality. Gypsy moth affects not only timber production through mortality and growth loss, but also aesthetics, recreation, wildlife habitat, water yield and quality, and future stands through changes in regeneration. Host preferences of the gypsy moth include oak, aspen, basswood, birch, and larch (table 2).

A pest need not be introduced or exotic to cause problems. Many native pests act in concert with environmental factors to cause dieback and decline. Oak decline is another insect-disease-environment complex that is causing widespread mortality of oaks throughout the Ozark Highlands in Missouri and Arkansas (fig. 6).

Table 2.—*Host preferences of the gypsy moth (from Gottschalk 1991).*

Preference level	Species
High	oaks, aspens, basswood, birches, larch, willows, apple, sweetgum
Moderate	beech, butternut, cherry, hickories, hemlock, cottonwood, pines, maples, yellow birch, chestnut, spruces, walnut
Low	ashes, cedars, locusts, junipers, sycamore, yellow-poplar, balsam fir

Figure 6.—*Oak decline is causing premature mortality of oak trees throughout the Ozark Highlands.*

Drought, *Armillaria* fungi, and wood boring insects in combination are causing severe mortality of oaks on over 400,000 acres in the Ozarks. Mature red oaks, including southern red oak, scarlet oak, and black oak, are particularly affected by oak decline, especially where they have replaced shortleaf pine on hot, dry sites that have thin soils. Dieback and decline diseases of trees are maladies related to the consequences of stress. Their incidence depends on adverse environmental conditions such as severe and extended droughts that create declines in tree vigor as well as subjecting stressed trees to the successful attack by opportunistic organisms. These diseases are progressive, and trees are debilitated several years before they die.

Three such opportunistic organisms are the fungus *Armillaria* and the insects two-lined chestnut borer and red oak borer. *Armillaria* can quickly colonize an entire root system and kill a tree after a severe stress such as defoliation or drought. The two-lined chestnut and red oak borers usually occur at low-level populations in oak forests throughout eastern North America where they infest branches and trunks of weakened oaks. However, borer populations can increase quickly to epidemic levels and cause widespread oak mortality following periods of drought or insect defoliation. Borers damage the wood in oak trees, reducing its value or making it unusable (fig. 7). John Kabrick, a North Central Research Station scientist, is developing management strategies and evaluating silvicultural practices for managing decline stands so they are less susceptible to catastrophic mortality in the future, and thus more productive.

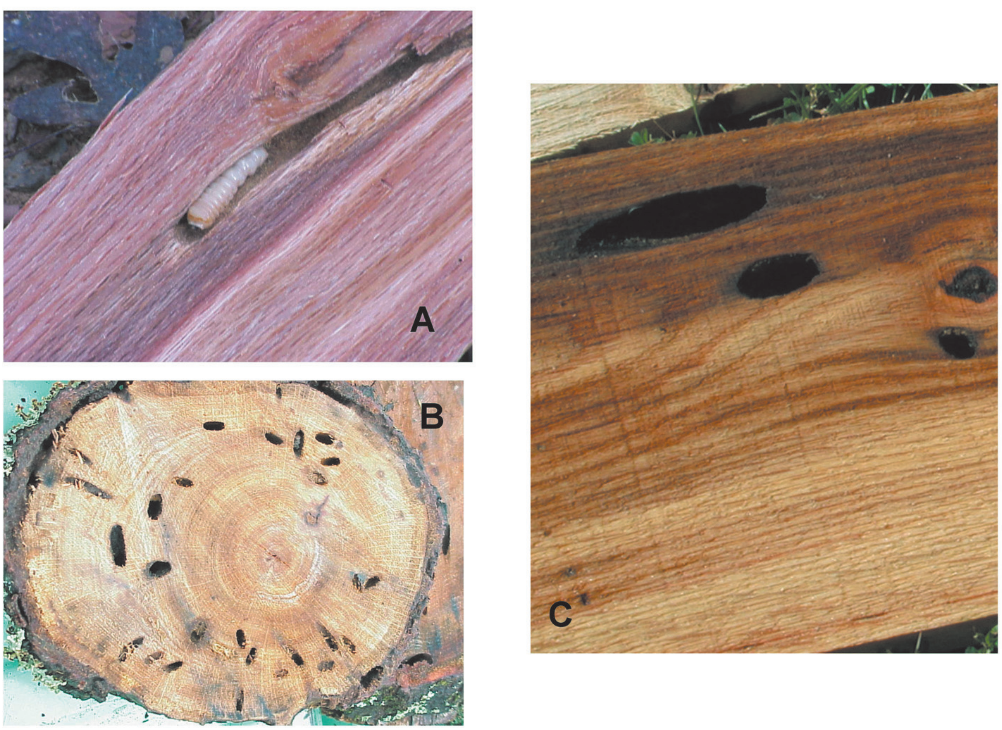


Figure 7.—*(A) Red oak borer larvae tunneling through oak wood. (B) Red oak borer tunnels in a cross section of black oak. (C) Red oak borer damage to oak lumber.*

Air Pollution and Carbon Dioxide—The FACE Experiment

Pollution is another factor that limits forest productivity. Due to human activities, especially auto emissions, concentrations of ozone (O_3) in the lower atmosphere are increasing. Levels of O_3 three or four times above background levels are common for short periods of time over much of the Eastern United States, and scientists predict a tripling of ambient O_3 concentrations within the next 30 to 40 years if current rates of increase continue. The direct impact of high O_3 levels is leaf damage that can result in early leaf fall; the indirect effect is reduced tree growth and even tree mortality (Dickson *et al.* 2000).

The interaction between increased levels of carbon dioxide (CO_2) and increased levels of O_3 are especially complex. Carbon dioxide at twice the current atmospheric concentration has the potential to increase productivity in many agricultural crops and many forest trees by 20 to 50 percent. However, elevated levels of O_3 in the lower atmosphere are likely to decrease tree growth. Do the effects of the two gases offset one another? Experiments conducted at the Free Air Carbon Dioxide Enrichment (FACE) site in Wisconsin suggest that elevated O_3 negated increased growth from CO_2 for several tree species. These FACE experiments are large enough so that the complex interactions of water, gas, energy fluxes, biological responses, and biogeochemical cycles can be studied together (fig. 8). Such studies are essential to better understand the effects of atmospheric pollution and global climate change on forest productivity.

Figure 8.—*An aerial view of the FACE study site near Rhinelander, Wisconsin. Each ring consists of 32 vertical vent pipes for emitting CO_2 and O_3 into the growing space for the experimental plant materials.*

Economics and Private Forest Landowners

Nonindustrial forest owners often consider timber production to be a low priority on their lands (Alig 1986). Bob Haight, North Central Research Station, and Greg Amacher, Virginia Polytechnic Institute and State University, are cooperating on a study to see if this priority might change as market values for timber increase. Previous studies, such as that conducted by Binkley (1981) in Vermont, suggested that stumpage price is a significant predictor of harvest behavior with private landowners, and thus prices and the resulting effects on harvesting behavior can be critical not only for predicting future timber supplies, but also for predicting the composition and structure of the future forest. Specifically, Haight and Amacher want to determine in their study how market signals, land and owner characteristics, and owner preferences affect landowners' decisions to harvest aspen forests.

Changing Composition of the Regional Forest

The changing composition of the regional forest can affect forest productivity. Throughout most of the region, maple is increasing in abundance, while aspen and birch are decreasing. Since 1935, for example, Michigan and Wisconsin have each lost nearly 2 million acres of the aspen-birch forest type (fig. 9), while both have gained about the same area in the maple forest type (fig. 10). On average, the growth of the early successional species, aspen and birch, is faster than that for the late successional species, sugar maple. These increases in maple and decreases in aspen could translate into lower productivity in the regional forest.

A very different situation exists in Minnesota. The area dominated by the aspen-birch forest type has remained the same during the 70-year period. Although the maple-dominated forest type is not extensive in Minnesota, the acreage doubled during this period (fig. 10). Very little management of maple is occurring in Minnesota at present.

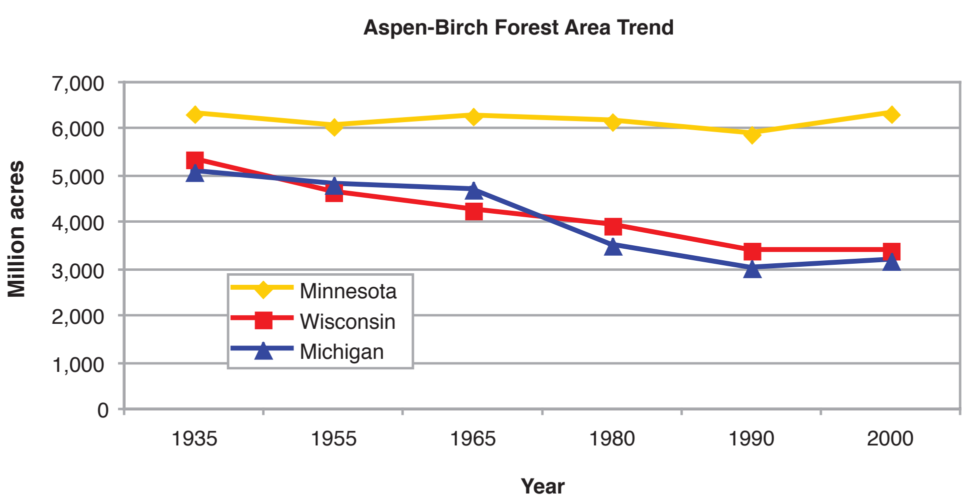


Figure 9.—*Changes in the area of the aspen-birch forest type in Michigan, Wisconsin, and Minnesota, 1935 to 2000. Aspen includes both trembling and bigtooth aspen; birch is paper or white birch. Adapted from Schulte and Crow 2003.*

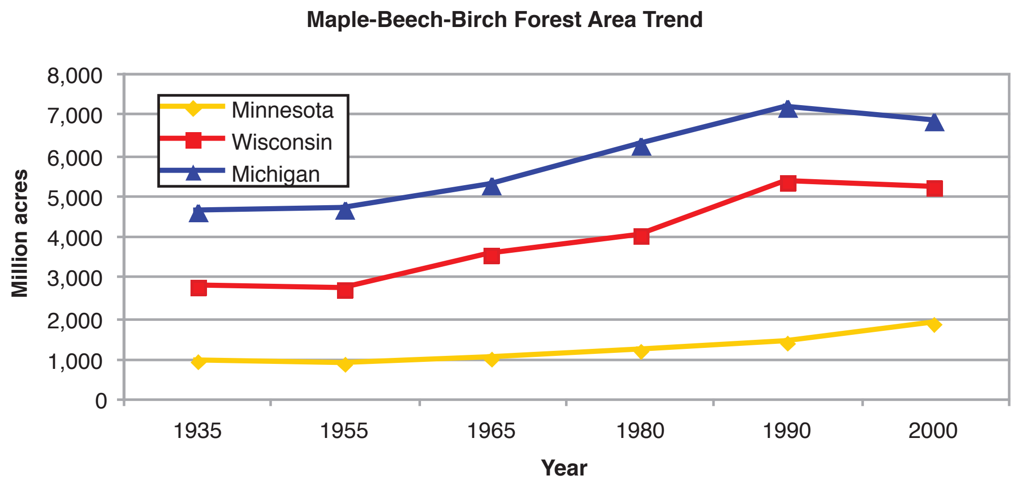


Figure 10.—*Changes in the areas of the maple-beech-birch forest type in Michigan, Wisconsin, and Minnesota, 1935 to 2000. The maple-beech-birch forest type is dominated by sugar maple. Adapted from Schulte and Crow 2003.*

The Urbanizing Landscape

Land use also affects forest productivity. Sprawling residential development, for example, creates challenges for resource managers. "Amenity" resources like forests and lakes attract developers and home buyers. But housing growth and supporting infrastructure such as roads, electrical rights-of-way, and sewer systems destroy wildlife habitat and fragment the landscape. Development has been widespread in the forested regions of northern Minnesota, Wisconsin, Michigan, as well as southern Missouri (fig. 11). In 1990, only 13 percent of all forests were located more than 15 miles from a high-density residential area.

Development creates smaller ownership units on the landscape, and at some point, it becomes uneconomical to produce timber from small forest ownerships. In an attempt to quantify landscape fragmentation in the Midwest resulting from changes in housing density, Volker Radeloff, Department of Forest Ecology and Management, University of Wisconsin-Madison, and Roger Hammer, Rural Sociology Department, University of Wisconsin-Madison, are working with scientists at the North Central Research Station to estimate the amount of landscape fragmentation, remaining forest interior habitat, and landscape connectivity for six study areas in northern Wisconsin. Early results can be seen in figure 11.

Small harvest units decrease timber volume per tract and increase harvesting costs per acre. In the Southeast United States, for example, Cubbage (1983) found that forest tracts smaller than 20 acres were economically inoperable. There is hope however. Although the mean size of holdings for nonindustrial private landowners in the Lake States is only 35 acres, the 20 percent of private owners with the largest holdings control more than half the acreage. Maintaining the integrity and productivity of these larger ownerships is critical to maintaining and increasing forest productivity in the Midwest.

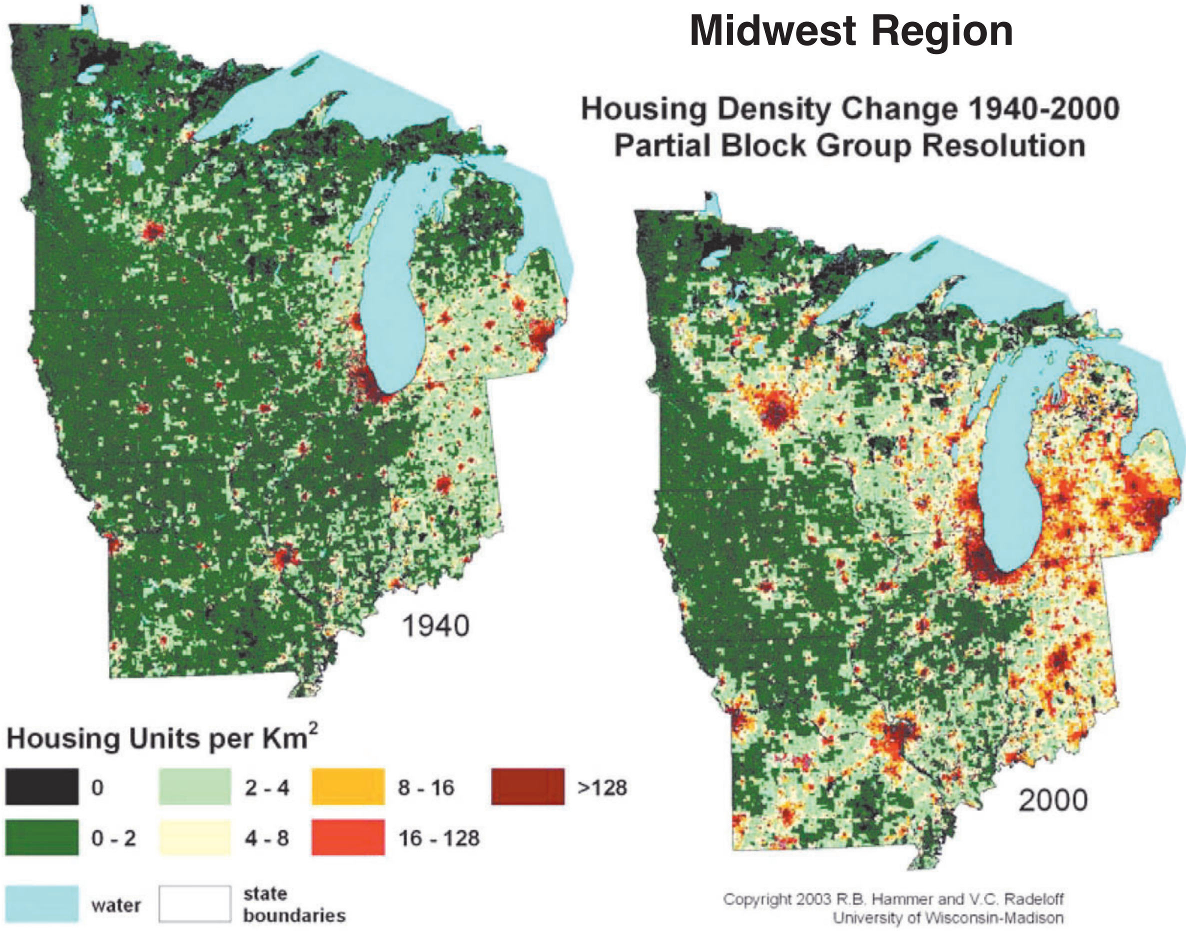


Figure 11.—*Housing densities in the Midwest region, 1940 and 2000.*

How Do We Enhance Forest Productivity?

Short Rotation Poplar Plantations

Many strategies can be used to increase forest productivity. For example, one strategy is to invest in intensive culture at carefully selected locations. A relatively high capital investment is generally associated with intensive culture because fertilization, irrigation, site preparation, control of competition, and planting of genetically improved stock are tools used in intensive culture, but the returns from intensive culture in terms of increased productivity can be substantial.

An attractive feature of intensive culture forestry is that it doesn't have to replace existing acres of natural forest. We have developed trees (cottonwoods and hybrid poplars) and special short rotation silvicultural systems that produce large amounts of wood on former agricultural sites. For example, recent tests of newly bred and selected poplars conducted in Minnesota, Wisconsin, and Iowa have demonstrated yields in excess of 17 Mg ha^{-1} yr^{-1} (the weight-equivalent of more than 6 cords per acre per year) at age 6 years after planting (table 3). Longer term studies have demonstrated that short rotation poplar plantings are sustainable over rotations of 8 to at least 12 years at many locations in the region.

The silvicultural system is intensive, but straightforward. An agricultural field is cultivated before planting. Dormant hardwood cuttings of select poplars are planted as unrooted cuttings. The cuttings then produce both a root and shoot system. Weed control is necessary, and protection from insects by chemical application or other means is often needed. Costs of production are high relative to wood produced from natural forests, but intensively cultured plantations have high yields, product uniformity, and year-round access to sites for cultural operations or harvest. The most significant feature of the system, however, is that more wood can be produced without impacting existing native forests. In Minnesota alone, about 2 million acres of farmland are considered excess to agricultural row crop production based on enrollment in the Conservation Reserve Program.

Table 3.—*Biomass yields (Mg ha^{-1} yr^{-1}) of control and newly developed clones of cottonwood and hybrid poplars at three test sites in the Midwest region. From Riemenschneider* et al. *2001.*

	Minnesota	Iowa	Wisconsin
Yield of best clone	6.79	16.84	17.16
Yield of standard	5.02	7.17	10.84
% Yield improvement	35.2	135.0	58.3

To illustrate how short rotation intensive culture system can benefit the region, we offer three "real-world" true examples of existing and developing projects:

Case 1:

Project: A large paper company operates an economically efficient paper mill, located far from the traditional woodshed. Feedstock is highly priced and supply is uncertain. The company establishes 25,000 acres of short rotation hybrid poplar plantations to provide 50 percent of the wood needed by the mill.

Benefit: Job security for several hundred mill workers. Increased and stable farm income. Continued profitable operations.

Status: The project is underway and R&D collaboration between the company, the North Central Research Station, and the University of Minnesota is continuing.

Management Notes

Practical information and recommendations for establishing, managing, and protecting short rotation poplar plantations can be obtained at http://www.ncrs.fs.fed.us/pubs

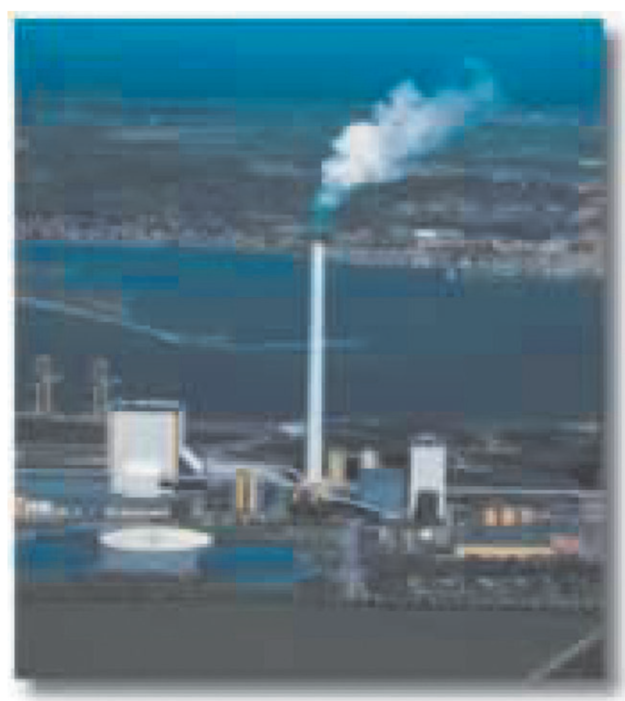
Case 2:

Project: A medium community is faced with the remediation of a closed landfill. One alternative to installing an expensive clay/artificial membrane landfill cap is to establish hydrologic control of the site by planting hybrid poplars over the entire 40-acre site.

Benefit: The community saves $15 million over a 20-year period based on the relative costs of plantation establishment vs. a clay and membrane landfill cap. The city avoids a budget crisis and the residents face lower property taxes.

Status: A 5-acre pilot test has been established and we are monitoring transpiration rates. The city and the Department of Natural Resources are currently negotiating a final remediation strategy. Scientists at the North Central Research Station provide scientific consultation and expert assistance with tree planting and maintenance.

Case 3:



Project: A State legislature mandates a large generating company to develop 200 megawatts of closed-loop (CO_2-neutral) generation capacity. Developers propose to build a 35-megawatts tree-fueled power plant as one component of compliance.

Benefit: A rural community receives an economic boost worth over $140 million (net present value of the first 20 years of operations) based on construction cost, farmland rental, tree farm operations, and plant operations and maintenance.

Status: Poplar clone trials have been established near the community. Expected financial performance of the feedstock and generating plant business centers currently is under evaluation. The North Central Research Station helps the developers understand expected growth rates, cost of production, and design of the overall feedstock production strategy.

Research being conducted at the North Central Research Station in Rhinelander, Wisconsin, is targeted toward breeding new, even more productive poplar varieties; refining vegetation management strategies; developing effective and environmentally acceptable insect pest control strategies; and understanding the full economic benefit of short rotation planting to rural communities. Intensive culture has its place as a production system within the broader landscape (cell iv, table 1) along with less intensive production systems (cell v, table 1) and reserves in which timber management is not practiced.

Hardwood Tree Improvement and Regeneration Center

Research being conducted at the Hardwood Tree Improvement and Regeneration Center (HTIRC), a cooperative effort between the North Central Research Station and Purdue University, is helping provide the genetic materials and the deployment strategies that will help increase forest productivity and the value of hardwood forests. For example, genetic materials are stored and catalogued in cDNA (cloned genes) libraries at the center. These libraries have samples of cloned RNA (genetic material that directs the production of proteins) that are sequenced and identified and thus available for tree improvement. Such libraries have long-term practical importance. In addition, genes identified and verified as being important for a particular trait can be used to genetically modify elite trees to transfer that trait to those cultivars. The HTIRC is developing the cloning and genetic modification technologies to make this possible.

Deployment of genetically improved trees requires research and development to improve seed production and handling, seedling quality, and plantation establishment. HTIRC is developing trellis systems that will encourage early flowering and seed production of elite cultivars. In addition, because hardwood seed has a short storage life, scientists are developing new methods to extend storage so that seed will be available when production is low. Plantation establishment success for most fine hardwoods is still low, partly due to seedling quality and partly due to after care. HTIRC staff are developing standards for seedling quality that will be adopted by nurseries, and they are testing herbicides for efficacy in plantation establishment.

Tapping the Potential of Red Pine Plantations

Red pine is one of the fastest growing tree species in the Lake States so increasing the abundance of red pine will increase regional forest productivity. A number of long-term studies conducted by scientists at the North Central Research Station tell us much about the growth and yield of this species. For example, we know that cubic volume growth of red pine stands increases with higher stand densities, but individual tree growth is higher at lower stand densities (Buckman *et al*. 2002). Thus, managers have the option of maximizing wood fiber production, or growing fewer trees and producing higher valued products such as lumber or poles, or some mixture in between. Site quality is a good indicator of economic profitability for red pine management. Better sites are more profitable despite higher establishment costs. Increasing the abundance of other conifer species, such as white spruce, white pine, and jack pine, would also increase wood productivity in the region's forest.

A number of long-term studies conducted by scientists at the North Central Research Station tell us much about the growth and yield of red pine species.

Productivity at the Landscape Scale

Another strategy involves making incremental improvements in forest productivity over large areas. Compared to intensive management, the second strategy has lower impacts (and costs) distributed over larger areas. Most traditional silvicultural systems—both even- and uneven-aged management—are examples of this extensive management strategy. Natural regeneration predominates in extensive management; and in addition to timber production, wildlife habitat, water production, recreation, and aesthetics are important.

Oak forests cover 154 million acres in the Eastern United States (Smith *et al.* 2001), with 20 million acres of this total located in the Upper Midwest (Spencer and Kingsley 1991). Improved management of these forests provides another opportunity to increase productivity and quality over large areas. Appropriate thinning of some oak forest can double timber outputs over a rotation, increase timber quality and value, mitigate insect and disease problems, improve vigor of residual trees, develop desirable advance tree reproduction, increase the aesthetic character of the forest, increase mast production and other benefits to wildlife, and increase species diversity (Johnson *et al.* 2002). Recommendations for appropriate management of oak are summarized in a new book *The Ecology and Silviculture of Oaks*, written by North Central Research Station scientists Paul Johnson, Steve Shifley, and Robert Rogers (currently professor at the University of Wisconsin-Stevens Point). This book provides state-of-the-art knowledge and a synthesis of research in oak-dominated ecosystems.

Guidelines for uneven-aged management (single-tree selection) in northern hardwoods developed at the North Central Research Station have been applied over thousands of acres in the Lake States and has resulted in improvements in both the quality and quantity of production in northern hardwood forests within the region. Even small improvements in productivity, say 5 or 10 percent, applied over large areas produce significant increases at the regional scale.

Management Notes

Practical information and recommendations for managing northern hardwoods, central hardwoods, and black walnut are available in a series of notes that are available online at the following addresses:

Northern Hardwood Notes:
http://www.ncrs.fs.fed.us/pubs/nh/NorthernHardwoodNotesTOC.htm

Central Hardwood Notes: http://www.ncrs.fs.fed.us/pubs/ch/CHNotestoc.html

Walnut Notes: http://www.ncrs.fs.fed.us/pubs/wn/walnutnotestoc.html

Information about silvicultural treatments, regeneration, stand management, growth and yield, stocking, economics, damaging agents, and wildlife habitat are available in these notes in an easy-to-read format.

Manager's Handbooks

A series of manager's handbooks were published by scientists at the North Central Research Station during the 1970s and 1980s for important forest types in the region, e.g., *Manager's Handbook for Oaks in the North Central States* by Ivan Sander, General Technical Report NC-37, 1977.

The purpose of this series was to present the latest and best information available for managing the forest types. The only problem is that the information is no longer the latest and best. So these popular handbooks are being updated.

A new joint publication between the North Central Research Station and the University of Minnesota is now available: Gilmore, Daniel W.; Palik, Brian J. 2006. *A revised managers handbook for red pine in the North Central region*. Gen. Tech. Rep. NC-264. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 55 p. Also available online: http://www.ncrs.fs.fed.us/pubs

Long-Term Site Productivity Study

Together with the climatic and biotic potential of vegetation, soil forms the foundation for forest production. The USDA Forest Service Long-Term Site Productivity (LTSP) cooperative study embodies the principle that soil processes controlling potential productivity involve physical, chemical, and biological interactions between soil porosity and site organic matter. Harvesting operations affect both the porosity of the soil and the soil organic content. Because responses to treatments are likely to differ depending on the physical environment, the LTSP study has been replicated on sites across the United States including the central (northern red oak, white oak, and shortleaf pine) and northern (aspen) forests of the Midwest region.

The objective of the LTSP study is to determine how changes in soil compaction and site organic matter affect forest productivity. The treatments include three levels of organic matter removal (harvest intensity) and three levels of soil compaction. Competing vegetation was also controlled on some sites.

As expected, responses varied among species and by sites, but some consistent trends have emerged. For example, eliminating plant competition with herbicides always leads to improved tree growth (often substantial increases). The use of herbicides has the potential to significantly increase wood production, although extensive use of herbicides is unacceptable to some people. The effects of soil compaction were apparent and significantly reduced tree growth in some cases. Overall, however, it appears that the majority of soils were coarse enough that compaction (by harvesting equipment, for example) did not produce detrimental changes in soil properties in the short term.

Life Belowground

Forests in the Midwest region store vast quantities of carbon, and carbon sequestration may become a central objective of future forest management because of concerns about global change. Management techniques and biophysical factors both impact carbon storage and sequestration in forests. Belowground productivity is especially important because approximately half the carbon stored in forests during photosynthesis is allocated belowground to roots and mycorrhizae, with large amounts of carbon stored in roots.

The North Central Research Station is conducting research on belowground processes because of their importance to forest productivity. Processes being studied include the fluxes and stores of carbon in the soil, nutrient cycles, and the role of soil organisms in these processes. These processes are vital for sustaining long-term forest productivity. More information about this work can be obtained from the Project Leader, Alexander Friend (afriend@fs.fed.us).

Managing Riparian Forests

Because of their location at the water's edge, riparian forests can be some of our most productive forests in the region. In a cooperative study with the University of Minnesota, Brian Palik and Randy Kolka of the North Central Research Station have established a study, Multi-Scale Functional Responses to Stand Manipulation in Riparian Forests. The study consists of four overstory treatments—control, high, medium, and low residual basal area—with each replicated in five watersheds in Minnesota. The treatment units, 25 to 50 acres in size, encompass small streams in upland hardwood forests and contain riparian management zones that extend 140 feet on each side of the stream. This research will help us understand the effects of management manipulations on the production of wood and storage of carbon in riparian ecosystems and demonstrates the benefits of proactive silviculture in riparian forests.

Most of the bottomland forests in the Midwest have been cleared for agriculture (fig. 12). After the Great Flood of 1993, that destroyed levees and degraded farmland along the Missouri and Mississippi Rivers, interest has been growing in reforesting abandoned crop fields on public and private lands (fig. 13). This catastrophic flood caused us to rethink how we manage our Big Rivers. Even though the Great Flood made many areas unsuitable for agriculture, these floodplains are still highly productive forest lands.

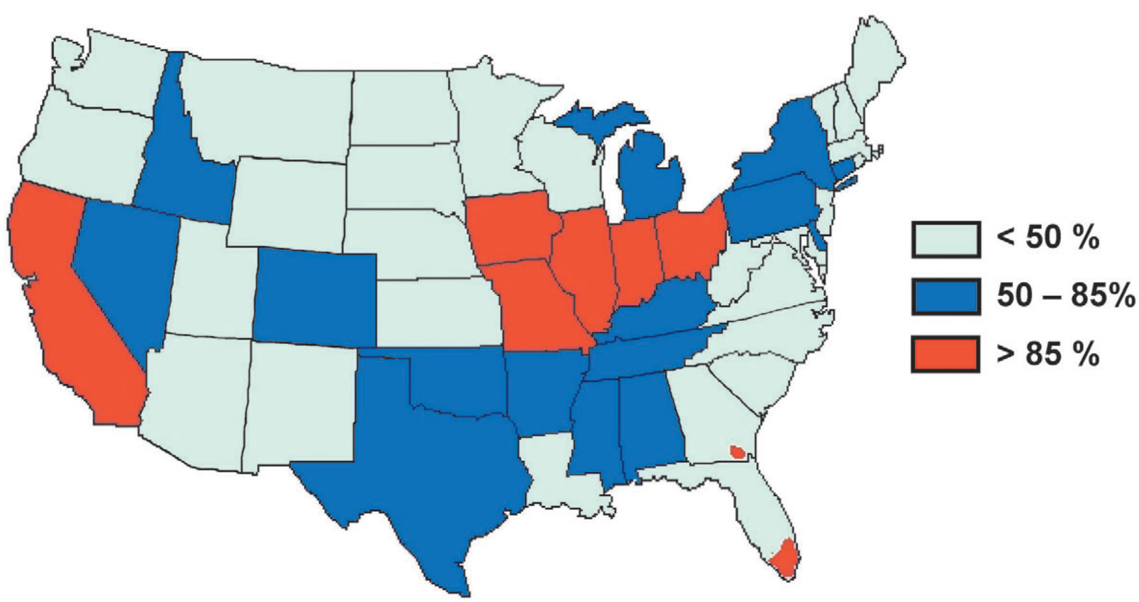


Figure 12.—*Percent loss of wetlands from the 1780s to 1980s in the contiguous United States (Dahl 1990). A significant amount of the wetlands lost in the Midwest was once forested floodplain.*

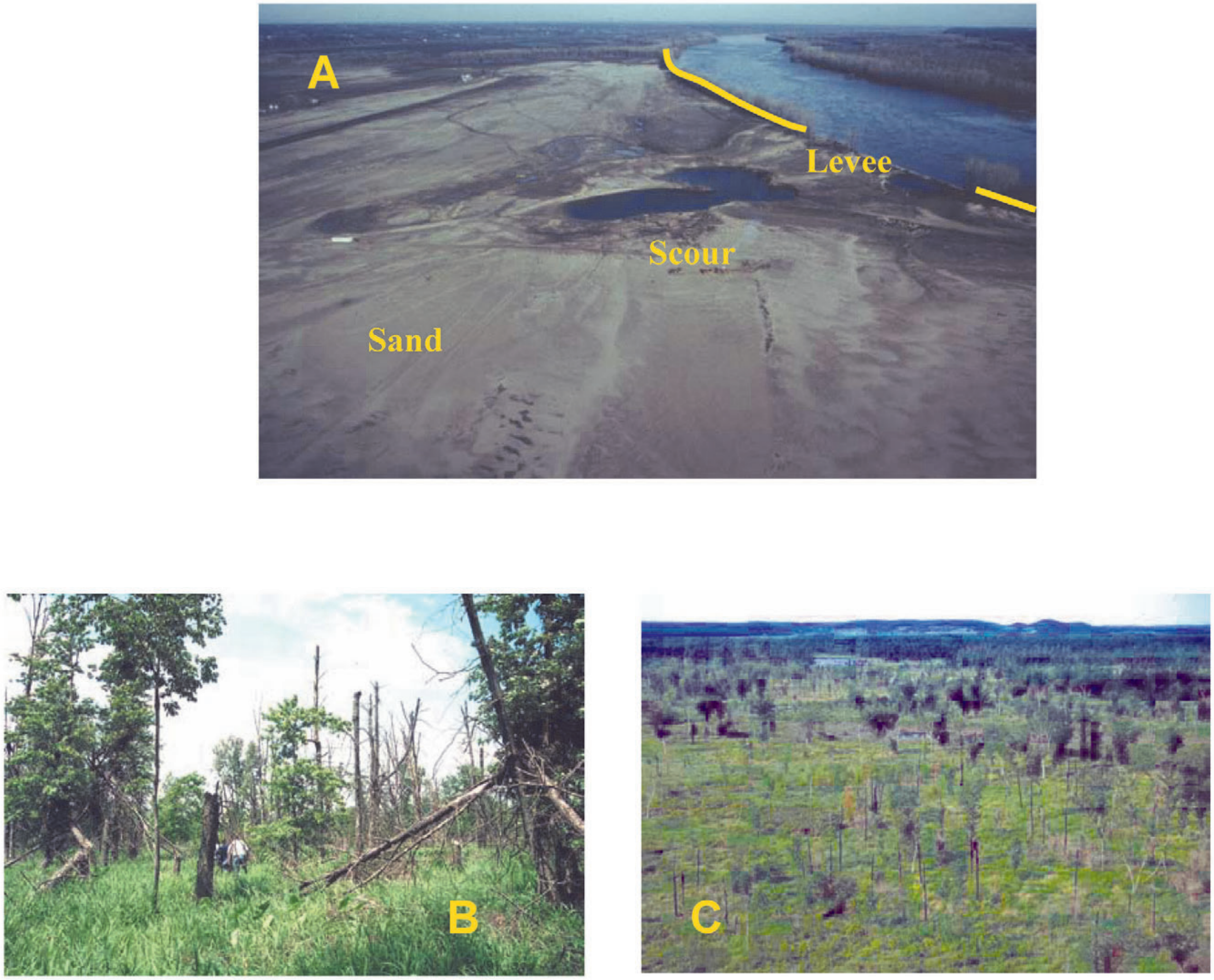


Figure 13.—*The Great Flood of 1993 (A) destroyed thousands of acres of bottomland farmlands by scouring crop fields or by dumping thick deposits of sand in fields. (B) Bottomland forests were decimated by the flood that persisted all summer in many places, killing up to 90 percent of mature trees. (C) The Great Flood turned one of the largest intact bottomland oak forests in Ted Shanks Conservation Area in the Mississippi floodplain into a wetland shrub-herbaceous patch, a tremendous loss of quality waterfowl habitat.*

Dan Dey and John Kabrick of the North Central Research Station are evaluating different methods of regenerating oaks and other highly valued species on abandoned agricultural bottomland crop fields (fig. 14). They have found that planting large container seedlings or large bare-root seedlings with a cover crop of redtop grass significantly improves survival and growth of seedlings, increases the competitiveness of the planted trees, and reduces animal damage to tree reproduction. Amazingly some of the 1- and 2-year-old container swamp white oak they planted produced acorns during the first year in the field. Normally it takes an oak 20 to 30 years or more before they begin producing acorns. Return of acorn or mast production to agricultural floodplains is important for forest regeneration and for wildlife such as migratory waterfowl, deer, and turkey. Acorn production is an important part of providing quality waterfowl habitat, which supports a very substantial recreational hunting industry.

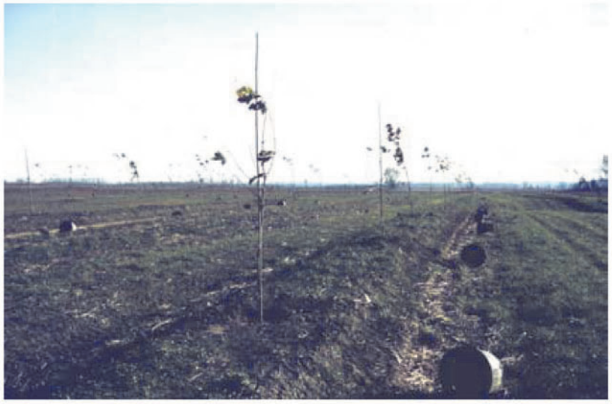


Figure 14.—*Successful tree regeneration on former agricultural crop fields can be achieved by planting large container seedlings in mounded soil and with a cover crop of redtop grass. In just a few years planted trees are dominant and free to grow.*

Dey and Kabrick are working with managers of State conservation departments; Federal agencies such as the U.S. Army Corps of Engineers, USDI Fish and Wildlife Service, USDA Forest Service, and USDI National Park Service; privately managed duck clubs; and private landowners to improve the quality and productivity of bottomland forests throughout the lower Missouri River basin and the upper Mississippi River valley. Use of their regeneration methods is increasing the amount of forest land in the region. The regeneration methods they developed can be used to establish trees for a variety of objectives including growing fine quality hardwoods in intensively managed plantations, sustaining acorn production in greentree reservoirs managed for waterfowl habitat, conducting agroforestry practices such as alley cropping and riparian buffers, and restoring bottomland forests to conserve native biodiversity (fig. 15).

From the Logger's Perspective

Despite the importance of the logging industry to continued forest productivity and timber supply, our knowledge about the logging sector in the Lakes States is limited. Most timber harvesting research has focused on the performance of specific logging equipment, the cost of implementing silviculture prescriptions, or the environmental impact of logging practices. In contrast, we have less of an understanding of logger demographics and the business environment in which they operate.

In a cooperative study, Mark Rickenbach and Thomas Steele of the University of Wisconsin-Madison, and Paul Gobster of the North Central Research Station are exploring the relationship among population growth in rural Wisconsin, Michigan, and Indiana, ownership parcelization, and logging opportunities based on responses from loggers. These scientists seek to understand how changing land tenure as measured by ownership and parcel size is changing the business of logging, and concurrently, the economic development opportunities in rural communities.

Figure 15.—*Regeneration methods are needed to establish and sustain a wide variety of riparian forest uses including (A) intensively managed plantations of fine quality hardwoods, (B) bottomland forests managed as greentree reservoirs for migratory waterfowl and hunting, (C) alley cropping in agroforestry systems, (D) riparian buffers for agroforestry production, water quality enhancement, and wildlife conservation, and (E) restoration of native bottomland forests.*

Where Do We Go From Here?

During the next 3 to 5 years, R&D in the Forest Productivity Integrated Program will be directed at improving our knowledge about current and potential productivity and the reasons why the two differ. Clearly, many kinds of R&D activities might be undertaken and so priorities must be set. To this end, we require a means of classifying possible R&D that permits options to be visualized and high priority activities to be selected.

Our model (table 1) casts various R&D activities within two dimensions: (1) scale (landscape to organism) and (2) intensity of management (extensive to intensive). Within this framework, we can focus and prioritize R&D. For example, we may choose to work at the organism level in conducting breeding or molecular research to address some biological constraints that limit the productivity of individual trees. These trees would most logically be planted on lands that are intensively managed where they are normally grown in plantations. It would be unlikely that improved and superior growing tree seedlings would be planted on lands managed at low intensity or on lands classified as reserve because of social, political, or economical constraints. Thus, research to improve the disease resistance or growth performance of tree seedlings would occur at the organismal level and silvicultural systems would be developed at the stand level to deploy these trees on lands suitable for intensive management where they occur across the landscape. This is but one example of an R&D effort to address the productivity of intensively managed forests that spans the spatial scales identified in the far left column of table 1.

In landscape-scale R&D it is important to recognize interactions among land use categories and the possible ecological, environmental, and social cumulative effects that occur often only at larger scales (e.g., watershed, landscape, regional). This is most clearly needed as we address the occurrence, distribution, and severity of wildfire, outbreaks of invasive species, and increasing human development and habitation of forested lands, all of which affect forest productivity.

Within our focus area (filled cells in table 1), the following R&D questions are high priority (order does not imply ranking):

- How can we develop improved trees for deployment on the most intensively managed forest and agricultural lands? (cell i)

- How do we improve stand management so that productive tree populations can reach their biological growth potential? How do we develop stand management practices suited to improving productivity on lands managed with medium intensity, especially those of private nonindustrial owners? (ii, iii)

- What other production systems such as mixed species silviculture and mixed or multiple cohorts need to be further developed? Where should those systems be deployed? (iii)

- How do we link deployment of high intensity management practices with other important features of the landscape such as wilderness, recreational lands, human settlement, and the urban interface in general? (iv to vi)

- What social trends (e.g., demographics, urbanization, ownership patterns) or attitudes enhance or limit opportunities to enhance forest productivity? What reconciliation processes are needed? (interacting quadrants)

- How can all of the above be used to formulate investment guidelines (how, when, and where) that will ultimately promote increased forest productivity?

Appendix 1.—NCRS-Sponsored Forest Productivity Research, 1999-2003

Year	Study title	NC contact	NC contact information	Cooperator/ contact	Cooperator information	IP funds
2003	From the logger's perspective: land tenure and timber supply in the Midwest Region	Paul Gobster NC-4902	pgobster@fs.fed.us 847-866-9311 x16	Mark Rickenbach, Dept. For. Ecol. and Manage., Univ. of Wisconsin-Madison	mgrickenbach@ facstaff.wisc.edu 608-262-0134	$57,892
2003	Implications of the changing composition and structure of forest ecosystems in the Great Lakes Region	Tom Crow Lisa Schulte NC-4101	lschulte@fs.fed.us 218-326-7122			$140,000
2002	Multi-scale functional responses to stand manipulations in riparian forests	Brian Palik NC-4101 John Zasada (retired) Randy Kolka NC-4101	bpalik@fs.fed.us 218-326-7116 rkolka@fs.fed.us 218-326-7115	Eric Zenner Univ of Minnesota	ezenner@umn.edu 612-625-3733	$57,000
2002	Assessing potential forest productivity in an ecological setting	Steve Shifley NC-4154	sshifley@fs.fed.us 573-875-5341 x232			$98,000
2002	Investigating economic drivers of forest change in the Lake States (estimating trends in landowner behavior regarding management of aspen in the Great Lakes Region	Bob Haight NC-4803	rhaight@fs.fed.us 651-649-5178			$80,000
2002	Forest fragmentation due to housing changes in the northwoods: spatial pattern of housing units through time			Volker Radeloff Dept. For. Ecol. and Manage., Univ. of Wisconsin-Madison	radeloff@facstaff. wisc.edu 608-265-6321	$95,988
2001	The role of forestry cooperatives in increasing forest productivity			Charles Blinn Univ. of Minnesota	cblinn@umn.edu 612-624-3788	$84,450
2000	Thinning aspen stands: creating heterogeneous landscapes for forest productivity, carbon sequestration, and increased tolerance of environmental stress	John Zasada (retired)				$50,000
2000	Silvicultural strategies for management of mixed-species stands for enhanced carbon sequestration	John Zasada (retired)		Klaus Puettmann Oregon State Univ.	klaus.puettman@ oregonstate.edu 514-737-8974	$25,000
2000	Evaluation of methods for regenerating mixed-species stands in the Missouri Ozarks	Dan Dey NC4154	ddey@fs.fed.us 573-875-5341 x225	Rose-Marie Muzika Dept. of For., Univ. of Missouri	muzika@missouri. edu 573-882-8835	$25,000
1999	The status of timber resources in the North Central United States	Steve Shifley NC-4154	sshifley@fs.fed.us 573-875-5341 x232	Neal Sullivan Miami Univ.	neal.sullivan@ gmail.com	$30,000

Appendix 2.—Forest Productivity Publications and Related Products

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Sabor, A.A.; Radeloff, V.C.; Hammer, R.B.; Stewart, S.I. 2003.
Relationship between housing density and timber harvests the Upper Lake States. In: Buse, L.J.; Perera, A.J., eds. Emerging ecological, economic and social challenges in the Great Lakes States. For. Res. Inf. Pap. 155. Sault Ste. Marie, ON: Ontario Forest Research Institute, Canada: 95-97.

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2006. **Forest productivity: producing goods and services for people.** Gen. Tech. Rep. NC-246. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 34 p.

Presents the progress made by North Central Research Station scientists working in the Forest Productivity Integrated Research and Development Program over the past several years. We discuss policy relevant research on assessing productivity, modeling potential, productivity, and improving productivity within the conceptual framework for research and development in the Forest Productivity Integrated Research Program.

KEY WORDS: forest productivity, midwest region, silviculture, assessment, social science.

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We believe the good life has its roots in clean air, sparkling water, rich soil, healthy economies and a diverse living landscape. Maintaining the good life for generations to come begins with everyday choices about natural resources. The North Central Research Station provides the knowledge and the tools to help people make informed choices. That's how the science we do enhances the quality of people's lives.

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