MANAGING RED PINE FOR TIMBER PRODUCTIVITY AND SUSTAINABILITY: LESSONS LEARNED OVER THE PAST CENTURY

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Abstract.—One hundred years ago the key problems in forestry were fire protection and regeneration. Little was known about the long-run productivity of managed red pine stands. Research programs initiated in the 1920's produced information on red pine growth and yield in response to management for a wide range of age, site, and stand conditions. This information was used to develop management guides to sustained high timber yields over long rotations. Over the years, we have learned some important lessons about red pine management. Currently the authors are refining and expanding existing models and simulation programs of red pine growth and yield.

Dr. Robert Buckman and I are midway through a review of previous growth and yield analyses of red pine (*Pinus resinosa* Ait.), on which several current stand management practices are based. In many respects, this is a continuation of work we and Dr. Robert Wambach began more than 40 years ago. At that time, we assembled information then available on red pine growth and yield in the Lake States to develop models for predicting stand behavior under a wide range of management alternatives. We now have a database many times larger than was available 40 years ago, spanning a wider range of sites, ages, and stand densities. These data, some with measurements dating back to the 1920's, were collected from 30 active and inactive studies provided by collaborators in Minnesota, Wisconsin, Michigan, and southeastern Ontario. We are testing the earlier red pine growth and yield models against these new data, and developing improved functions to better represent this expanded data set.

Today we would like to share with you some of the impressions coming out of our current work. These analyses reinforce several of our older conclusions, indicate new findings, and suggest challenges remaining for the next generation of researchers.

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But first, because the conference deals with sustainability of timber production, we would like to take a brief look at the changes that have taken place in our knowledge of red pine management over the past century. Here we emphasize three activities that are especially important in managing red pine for sustainable timber production: protection, regeneration, and stand management.

IN THE BEGINNING

In 1898, the pine forests that once covered large portions of Minnesota were being logged off rapidly. Concern was growing about the sustainability of timber production in Minnesota, the last of the Lake States to be logged off, and about the future of the timber industry. White pine (*Pinus strobus* L.) and red (Norway) pine were the dominant species in the timber trade, and lumber was the primary product. Substantial amounts of timber were periodically lost to wild fires and unconstrained burning for land clearing. Knowledge about establishing and managing red and white pine was scanty, and based largely on limited experience in the northeastern states and with other species in Europe. At this time the major concerns in managing red pine were fire protection and regeneration. Let us illustrate with examples from Minnesota.

Fire Protection

In 1898, organized fire protection for Minnesota forests was in its infancy. In 1895, following the disastrous Hinckley fire in Minnesota in 1894, the Minnesota legislature passed an act, "To Provide for the Preservation of Forests of this State and for the Prevention and Suppression of Forest and Prairie Fires" (Minnesota 1896). This act established the Office of Chief Fire Warden, with responsibility and authority for organizing fire suppression activities in the state. It set up a system of fire wardens throughout the state, and established duties, rules, and penalties. The act allowed only $5,000 for expenses in preventing and extinguishing forest and prairie fires in the state (Minnesota 1896, p.7).

C.C. Andrews was appointed as the first Chief Fire Warden, and held this position well into the 1900's. His annual reports indicated that fire wardens were active in fighting fires in their area. Fire protection remained an important job of forest managers throughout the century. Even today, although we better understand the role of fire in northern forest ecosystems, protection against unwanted wild fire remains of key importance. Following studies in the 1960's on the use of fire in site preparation and control of understory vegetation, we now recognize its potential as a tool in the management of red pine.

So, what have we learned about fire protection?

Protection from wild fire was indeed the starting point for forest conservation, not only in the Lake States, but elsewhere in the U.S. Fire prevention and wildfire control techniques have greatly improved over the past century and remain a centerpiece of sound forest sustainability.

Over the last half century, increasing attention has turned to fire ecology and the role of fire in management of forests. Both research and the application of prescribed fire have been intermittent and uneven. More research is needed. But the principal obstacles seem to be operational ones—infrequent and unpredictable burning weather; excessively cumbersome administrative obstacles; inadequate recognition for successful use of fire; excessive sanctions for faulty use; need to enhance skill levels in use of fire; among others.

In addition to fire protection, we should not overlook the importance of insects, diseases, and other natural and human agents in forest protection, but with limited time we have to leave this important topic to others.

Regeneration

In addition to fire prevention and suppression, the Chief Fire Warden was required to "... investigate the extent of the forests in the state ... the method used, if any, to promote the regrowth of timber, and any other important facts relating to forest interests ...". In his annual reports beginning in 1895, Andrews vigorously proposed programs to protect, reforest, and manage under scientific forestry principles the forest resources of the state (Minnesota 1896). He argued for a major program by the state government to acquire and reforest large tracts of forest land in northern Minnesota to help achieve a sustainable high level of pine timber output, particularly white and Norway (red) pine. During 1898, he contracted with Dr. C.A. Schenck, the Superintendent of the Biltmore Forest in North Carolina, to visit Minnesota and recommend a program "For reforestation of waste lands in Minnesota." Dr. Schenck analyzed the potential and recommended a plan to reforest 25,000 acres a year for 80 years by planting white pine to create conditions of a normal forest, with a sustainable timber output (Minnesota 1899).

Although sustainable forestry for pine timber production appeared feasible, it was generally agreed that private industry could not afford to reforest and manage the cutover lands under the existing system of forest land taxation (Frederick Weyerhaeuser in Northwestern Lumberman; March 12, 1898; page 5). The job of reforestation would have to be left to the state or federal government. Yet year after year, Andrews' pleas for a reforestation program in Minnesota to sustain long-term timber production produced no response from the legislature.

Much of the early work on the silviculture of red pine understandably addressed questions of regeneration. In Minnesota, the Morris Act of 1902 by Congress required that 5% of the volume of all standing timber on the Minnesota National Forest (now the Chippewa N.F.) be left as seed trees (Zon 1912). This was amended in 1908 to require that 10% be left. Cutting on the Minnesota National Forest under this act began in 1904, which happened to be a good seed year, and reproduction of red pine appeared to be good in many areas. However, several poor seed years followed, and pine reproduction failed.

In an early appraisal of regeneration success under this act, Zon (1912) observed that although timber harvests were made every year, the good seed years needed to regenerate the stand occurred infrequently. If a good seed year doesn't occur immediately after logging, then competing vegetation will occupy the site, and unless removed, will make natural regeneration unlikely. Richmond (1914) and Truax (1915) in their studies of regeneration in the Minnesota National Forest reached similar conclusions. Richmond argued for more reliance on planting to ensure full restocking of the land after cutting. Several decades later, Eyre and Zehngraff (1948) reviewed the evidence and concluded that the seed tree method of regeneration mandated by the Morris Act was largely unsuccessful.

Plantation forestry also had its start early in this century. In 1901, H.H. Chapman, then superintendent of the University of Minnesota Agricultural Experiment Station at Grand Rapids, MN, established a 35-acre red pine plantation on the grounds of the Grand Rapids Station, using transplanted wild seedlings. Parts of the growth records of that plantation, which is still being maintained today, are used in our current analysis. Additional red pine plantations were established in the Lake States beginning about 1910. Several of these early plantations, including Bosom Field in Michigan (1913), Birch Lake in Minnesota (1916), Buck Creek in Michigan (1918), and Croton Dam in Michigan (1929), were later used for long-term thinning experiments and provide valuable data for our analyses.

What have we learned about regeneration over the past century?

About natural regeneration.—Over the past 100 years, we have improved our understanding of the factors that affect successful natural red pine regeneration, but we face obstacles in applying what we know. Successful timing of tree harvesting and effective site preparation with a good seed year may result in abundant regeneration, but this may occur infrequently. Where natural regeneration does occur, we have little control over the density and spacing of established trees. The resulting stand may require precommercial thinning of densely stocked areas, and an ability to tolerate nonstocked areas. Reliable natural regeneration of red and white pine, especially on medium and better sites, remains one of the major unresolved problems in the Lake States.

About artificial regeneration.—On the other hand, we have learned much about artificial regeneration, including nursery management, site preparation requirements, and proper planting practices. We know that proper site preparation is essential, and have explored the potential of fire as a means of site preparation. We know that followup treatments and release from competing vegetation are critically important to improve survival and achieve rapid early growth in planted stock. Intensive early stand tending effectively increases apparent site quality by several index feet. Questions remain about the difficulties in establishing red pine through planting, especially on the very best sites, and about reducing costs and satisfying environment concerns. Still, large areas of red pine stands being managed today in the Lake States are plantations that were successfully established this century.

Stand Management

Few guides to red pine management were available early in the century. In 1896, Samuel B. Green and H. B. Ayres estimated the potential productivity of cutover timber lands in Minnesota. They concluded that rapid growth in both volume and value of pines and other conifers could be achieved with management (Green and Ayres 1896).

In 1898, Samuel B. Green, Professor of Horticulture and Forestry at the University of Minnesota, published his textbook, "Forestry In Minnesota" (Green 1898). Although not specifically addressing red pine management, Green discussed what had to be done to maintain timber production in Minnesota, including fire protection, regeneration of stands after cutting, and other forest management practices.

In 1898, C.C. Andrews published his Third Annual Report of the Chief Fire Warden for the Year 1897, in which he described what he called "Leading Principles of Forestry." One of these principles was:

> "... that the forest must be continuous; that it should always furnish a sustained yield; that no more timber should be taken out of it in a year or in a series of ten or twenty years than grows in the entire forest the same period; so that in a hundred years hence as much can be cut in a year as can now be cut in a year." (Minnesota 1898, p.26)

In 1914, Woolsey and Chapman produced the first comprehensive guide to the management of red pine in the Lake States. This was USDA Bulletin 139, "Norway Pine in the Lake States" (Woolsey and Chapman 1914). Based primarily upon field observations and experience, it provided recommendations on regeneration, growth and yield, stand management, and intermediate cuttings. For example, Woolsey and Chapman suggested first trying to get natural regeneration if possible through some form of partial cutting, but then to resort to artificial reforestation by planting if needed. They recognized that diameter growth of a tree is strongly influenced by soil quality and stand density, and recommended early, light, and frequent thinnings to promote diameter growth. They recommended rotations ranging from 60 to 140 years, depending on stand and market conditions.

RESEARCH ON RED PINE OVER THE PAST CENTURY

Research programs in the Lake States have contributed greatly to our understanding of red pine growth and yield and development of management guides. A recent comprehensive listing of publications related to the management of red pine contains more than 550 publications produced during the past century.

Although observations and measurements of red pine trees and stands in Minnesota and elsewhere were made in the early part of this century (e.g., Green and Ayres 1896, Zon 1912), there was no formal program of research on red pine in the Lake States at that time.

In 1918, Canada's program of research on red pine began with the establishment of Permanent Sample Plot 1 in a 40-year-old stand of eastern white pine (*Pinus strobus* L.) and red pine. The program of red pine research at Petawawa (now the Petawawa National Forestry Institute) continues to this day (for a review, see Stiell 1994).

In 1923, 75 years ago, the Lake States Forest Experiment Station (now part of the North Central Forest Experiment Station) was established by the USDA Forest Service. Two years later, it began a program of research on red pine growth and yield by establishing Bena Plots 1-4 (in Minnesota) in a 100-year-old stand. The intent was to study natural regeneration in relation to overstory density, but these plots later provided valuable growth and yield information. Although the study has been terminated, data are used in our current analysis.

By the mid-1920's, additional studies of intermediate stand management practices were established by both the Lake States Forest Experiment Station and the University of Minnesota. These included precommercial thinning in natural red pine stands. During the 1930's additional studies on red pine release, pruning, and thinning were installed. Much of what had been learned from existing red pine research—accelerated tree planting, precommercial and commercial thinning, release from competing vegetation, and pruning—were applied by the Civilian Conservation Corps and other depression-era programs to enhance public forestry in the Lake States. Little new red pine research was initiated during World War II, except for several sample plots installed in two old-growth stands in Minnesota: a 144-year-old stand at Marcell, and a 125-year-old stand at Lake 13 on the Chippewa National Forest. These studies are still active and, together with Bena Plots 1-4, provide useful growth information in stands older than 150 years, despite limitations in study design.

Fifty years ago, in 1948, "Red Pine Management in Minnesota" by Eyre and Zehngraff (1948), was published. Based on information available up through World War II, this became the authoritative guide to the management of red pine in the Lake States.

In the 1950's and early 1960's, research on red pine by the Lake States Forest Experiment Station and its cooperators was reexamined and strengthened. Replicated, sharply focused, and contrasting thinning experiments in both planted and natural stands supplemented and replaced earlier studies. These included density studies in intermediate-aged natural and planted stands, plantation spacing experiments, cutting methods (e.g., thinning from above or below), row thinning, and cutting cycles. Although some of these studies were eventually terminated, most continue today. Many provide more than 40 years of repeated measurement and treatment. Most include unthinned plots, which enhance an understanding of tree and stand behavior at high densities in the absence of cutting disturbance. Studies of genetic variation of various tree species initiated during this period eventually showed the lack of genetic variability in red pine.

During the 1970's and 1980's, studies of site index and volume growth comparisons with other species indicated the high productivity of red pine in comparison with other major species in the Lake States.

Similar red pine studies, virtually all in planted forests, were initiated by Fred Wilson of the Wisconsin DNR, Maurice Day and Victor Rudolph of Michigan State University, Will Stiell and others at the Petawawa Forestry Centre in Canada. Studies of red pine growth by other individuals and industry have contributed to the store of information about the response of red pine to management. Some of these studies have been used in our current analysis of red pine growth and yield, while others provide an independent source of information to check results of our current analysis.

DEVELOPING GROWTH MODELS TO EXPLORE MANAGEMENT OPTIONS

The earliest red pine growth and yield estimates came from normal yield tables, in which age and site index were variable, and stand density was assumed to be normal or full stocking. For example, Eyre and Zehngraff (1948, p.32) presented normal yield tables for unmanaged red pine stands for three site classes. However, they could offer only one table for a managed red pine stand on an average site, and remarked that it was probably one of the first constructed for any species in the country.

The ability to construct mathematical models of growth and yield covering a range of sites, ages, and stand densities provided a major advance. In the late 1950's, Robert Buckman developed one of the earliest mathematical models available for any tree species. Besides developing compatible equations describing growth and yield of red pine, he provided a set of yield tables for stands of red pine thinned to varying stand densities for a range of ages from 30 to 150 years and for site indexes from 45 to 60. Based on 235 red pine permanent growth plots in Minnesota, with 324 measurement periods, this original analysis (Buckman 1962) is dwarfed by the almost 3,800 plot measurement periods available for use in our current analyses.

To fill in the information gap about growth and yield in young stands, Robert Wambach (1967) developed a mathematical model of growth in young red pine plantations throughout the Lake States. This model covered a wide range of site conditions and initial stocking for ages up to 35 years.

In the early 1970's, Lundgren (1985) integrated the two sets of mathematical functions and developed a computer program to simulate growth and yields in red pine stands under various management regimes. REDPINE, as the program was called initially, ran on a mainframe computer and could be used to explore the product yield outcomes of alternative thinning strategies over a wide range of site and initial stand conditions (Lundgren 1981). The program was later modified for personal computers, as RPAL by Dr. Carl Ramm (1990), at Michigan State University. The most recent user-friendly version of this red pine projection program, RSPIM, was developed this year by Dr. Dietmar Rose of the University of Minnesota. These programs all incorporate the original mathematical growth and yield functions of Buckman and Wambach. As our current work proceeds, existing programs will be modified to incorporate new mathematical functions of growth and yield. We fully expect the equations to cover a wider range of ages, stand densities, and site indexes than was possible with our earlier work.

Buckman's original growth functions covered a relatively narrow range of sites, from SI45 to 60. Subsequent tests using independent sets of published data on red pine yields for sites up to site index 90 indicate that projections beyond the limits of the original data appear to be surprisingly good with no significant bias (Lundgren 1983). Thus, although the new functions we are developing will provide more precise estimates of growth responses for particular age, site, and density classes, we do not expect their use to result in major changes in overall management recommendations.

WHAT WE HAVE LEARNED ABOUT RED PINE MANAGEMENT

Because site and stand conditions can vary so much, our brief paper can only draw some general conclusions regarding the lessons we have learned about red pine management over the past century and emerging from our current work. Nevertheless, we will try to briefly summarize what we believe are some key points to keep in mind about red pine management for timber production and sustainability. Many of the conclusions we have reached are based on analyses using the original simulation models of red pine growth. Subsequent testing of these models have supported their use in this manner. We will first focus on some lessons we have learned from our previous studies that appear to stand the test of time; we will then call attention to some key findings from our current analyses; and finally we will suggest a few of the challenges that still remain for future forestry research.

Previous Lessons Learned About Red Pine Management

Lesson 1. Good Sites Are More Productive. The better the site, the taller the trees. Also, the better the site, the more basal area per acre. Thus, because Volume = k(Basal Area)(Height), the better the site, the greater the volume of timber produced.

Lesson 2. Initial Stocking Levels Affect Stand Growth and Tree Diameter. The higher the initial stocking, the sooner the site is fully utilized, and the higher the productivity of the stand. BUT—The more trees per acre, the slower the diameter growth and the longer the wait until trees become merchantable. ALSO—There are diminishing returns from additional trees per acre. There is a tradeoff between the quantity and quality of trees.

Lesson 3. Initial Stocking Levels Affect Costs. Planting fewer trees per acre reduces establishment costs. Planting fewer trees per acre may reduce release costs. More trees per acre increases the number of trees per unit of volume, and may increase timber harvesting costs.

Lesson 4. Timing and Intensity of Thinning Affect Amount, Quality, and Timing of Timber Product Outputs. Volume growth rates in red pine stands vary for different stand densities and ages. However, often the difference is relatively small over a fairly wide range of stand conditions. Thus, there is considerable flexibility in scheduling the timing and intensity of partial harvest cuts.

Lesson 5. Rotation Ages Can Be Flexible. Rotation ages of even-aged red pine stands can be varied over a wide range to suit the owner's needs and objectives. Periodic partial harvesting can keep stands productive for up to 200 or more years, simulating old-growth forests. Longer rotations reduce the frequency of site disturbance caused by stand regeneration.

Findings From Current Analyses

Our current analyses of red pine growth and yield are still underway, but some preliminary findings are emerging:

Growth in young stands. Growth in very young stands is much more responsive to early stand densities than we realized earlier. Two of the 30 studies, the Spooner and the Black River Falls plantations, were aimed at this specific question. At age 22 years from seed, the stands at various spacings had accumulated the following basal areas (square feet per acre):

	Spacing (feet)			
	5x5	7x7	9x9	11x11
Spooner	174	142	131	101
Black River Falls	175	118	113	66

These large basal area differences tend to lessen with advancing age. However, for those who wish to manage for fiber production, there will be challenging questions about initial planting densities and costs compared to higher fiber yields 20 to 30 years later. We hope to develop better procedures to estimate early stand responses, but questions will remain because red pine stands are so dynamic at these early ages.

Thinning methods. Four of the long-term studies involved thinning methods (thinning from above, above and below, and below). It is apparent at this stage in our analysis that there is little difference in growth rates at high densities (120 square feet per acre of residual basal area or more). At lower residual stand densities (60 to 120 square feet per acre), there appears to be somewhat higher growth for stands thinned from above. This finding challenges most conventional practices in red pine silviculture, where thinning from below is traditional. However, thinning methods also profoundly affect tree sizes and numbers of stems in the remaining stand. Thus, forest managers have considerable flexibility in products harvested in thinning operations.

Challenges For the Future

From past and current work, three major challenges emerge that deserve attention by the next generation of red pine research:

Natural regeneration. Despite a century of research and field trials, natural regeneration of red (and white) pine remains an elusive goal, especially on medium and better sites. Without doubt, fire remains one of the major ecological factors in successful regeneration, but erratic seed crops, unpredictable climatic variations, and other factors contribute as well.

Young stand behavior. We find that measurable basal area growth begins at about ages 7 to 10 years from seed, and culminates only a few years later at approximately ages of 15 to 20. This culmination of early basal area development is so rapid and so high that characterization of growth in this period alone would qreatly enhance our ability to predict stand behavior not only in young but also in older stands.

Landscape-level questions. The role of red (and white) pine in landscape-level questions deserves more study. For example, would habitats for wildlife be enhanced if conifer stands were present in large expanses of aspen and hardwood? Conversely, what are the opportunities to enhance wildlife habitat in and around coniferous stands, while still maintaining high productivity?

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Billions of tons of plastic have been made over the past decades, and much of it is becoming trash and litter, finds the first analysis of the issue. Video Player is loading. Play Video.Â Companies like Coca-Cola used to collect 98 percent of their bottles, and new entrepreneurs are learning from their tactics. Science. Toxic â€˜forever chemicalsâ€™ more common in tap water than thought, report says. Lean and Green, a student initiative that strives to promote sustainability on campus through environmentally friendly and healthy diet choices, conducted a study that showed students donâ€™t fully understand the impact their eating habits have on the environment. The livestock industry of chickens, cows and pigs produces more greenhouse gas emissions that all cars and trucks combined, according to Greenpeace. So as we eat more meat, the demand for meat likewise goes up and increases those gases. But when we eat more meat alternatives instead, like nuts or tofu, we can make a big difference. Acc

The paper approaches the task of forecasting 20 years into the future by extracting relevant precedents from the growth in labor productivity and in MFP over the last seven years, the last 20 years, and the last 116 years. Its conclusion is that over the next 20 years (2007-2027) growth in real potential GDP will be 2.4 percent (the same as in 2000-07), growth in total economy labor productivity will be 1.7 percent, and growth in the more familiar concept of NFPB sector labor productivity will be 2.05 percent. The implied forecast 1.50 percent growth rate of per-capita real GDP falls far short Compiled by 145 expert authors from 50 countries over the past three years, with inputs from another 310 contributing authors, the Report assesses changes over the past five decades, providing a comprehensive picture of the relationship between economic development pathways and their impacts on nature. It also offers a range of possible scenarios for the coming decades.Â The Report also presents a wide range of illustrative actions for sustainability and pathways for achieving them across and between sectors such as agriculture, forestry, marine systems, freshwater systems, urban areas, energy, finance and many others. Future outlook. Summary of lessons learnt. Information: Access.Â Estimating defoliation of Scots pine stands using machine learning methods and vegetation indices of Sentinel-2. European Journal of Remote Sensing, Vol. 51, Issue. 1, p. 194.Â The fading process progresses, with foliage changing from yellow to red over the subsequent spring and summer in the year following attack (Amman Reference Amman1982). Up to one year after being successfully attacked, more than 90% of killed trees will have red needles; this is known as the red-attack stage (Wulder et al.