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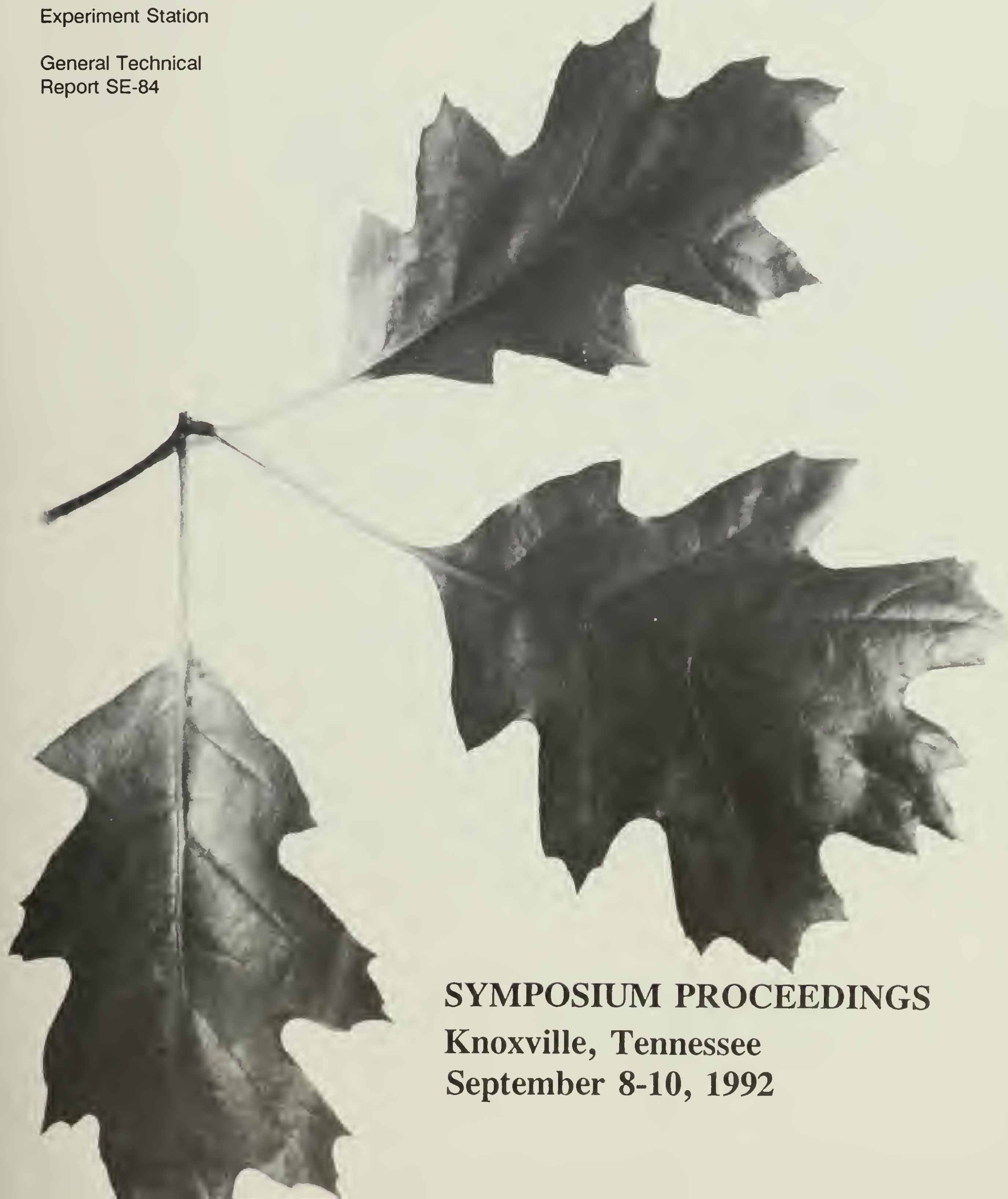
Southeastern Forest
Experiment Station

General Technical
Report SE-84

Oak Regeneration:

Serious Problems
Practical Recommendations



SYMPOSIUM PROCEEDINGS
Knoxville, Tennessee
September 8-10, 1992

Loftis, David; McGee, Charles E. eds. 1993. Oak Regeneration: Serious problems, practical recommendations. Symposium Proceedings; 1992 September 8-10; Knoxville, Tennessee. Presented by the Center for Oak Studies. Gen. Tech. Rep. SE-84. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 319 pp.

Twenty six papers dealing with the problems and opportunities associated with artificial and natural regeneration of the oak resources are presented. Subject matter, titles of papers, and authors were carefully selected to provide the best available coverage of the state-of-the-art of oak regeneration.

ERRATA

In the preparation of camera copy for GTR SE-84, *Oak Regeneration: Serious Problems, Practical Recommendations,* more than half the literature citations were dropped from the paper by Hodges & Gardiner (page 54 ff.). Beginning with the final citation on page 65, the remainder of the list of citations is provided herewith.
—SEFES, February 1994

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Oak Regeneration:

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Symposium Proceedings

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Editors
David L. Loftis and Charles E. McGee

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Preface

These Proceedings are in partial fulfillment of a Technology Transfer Plan on oak agreed to by a number of parties in 1988. The plan called for a symposium on oak regeneration. Oral presentations based upon the papers in these proceedings were delivered on September 9th and 10th, 1992, in Knoxville, Tennessee.

A Core Team was selected to administer and implement the Technology Transfer Plan, and this Core Team served as the Steering Committee for the symposium. An outline for the symposium on oak regeneration was developed and approved by the Core Team, which then approved the subject for each paper and decided upon the most appropriate author to write and present the paper. The primary objective was to carefully structure a program that would address the problems and opportunities associated with oak regeneration. A secondary objective was to evaluate the procedures used in this effort as means of achieving technology transfer.

Each of the papers in the Proceedings received technical and editorial review; all reviewers'comments were made in the form of suggestions, however. Therefore, the content and accuracy of each paper is the responsibility of the author. Overall, the Core Team feels that these papers accurately reflect the state of the art for oak regeneration today. The Team suggests that each reader take into account that some conclusions and recommendations are reached and made in a very dynamic environment. It is expected that this symposium fills the need for "results now."

The Core Team wishes to thank the sponsors, authors, and reviewers. The Team especially appreciates the moderators who not only added their own expertise and credibility to the program but did an excellent job keeping the demanding schedule intact. Moderators included Jack Pitcher, Hardwood Research Council; Bob Rogers, University of Wisconsin; Bill Mahalak, Michigan Department of Natural Resources; Tony Parks, Anderson Tully Company; Gary Schneider, University of Tennessee; Randy Rousseau, Westvaco Corporation; and Charles E. McGee, Center for Oak Studies.

The Core Team especially thanks Bill Hamilton (USFS-Retired) and Tami Steppleton (USFS), for their dedicated, persistent efforts to design, assemble, and format these Proceedings.

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The Oak Regeneration Problem

An Historical Perspective of Oak Regeneration

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ABSTRACT

Concerns about oak management in the middle ages led to forest ordinances in France designed to ensure oak establishment. Oak was an early export from the American colonies because it was scarce and expensive in England. Probably the first government sponsored forest research in the United States was attempts in Florida in the early 1800's to establish live oak (*Quercus virginiana*) for shipbuilding. With the advent of technical forestry in this country there were references in early papers and textbooks to oak regeneration and the shelterwood method. This interest was primarily for academic study and followed European descriptions, but some of the earliest oak regeneration research related to concerns about areas without advance reproduction.

In the late 1930's understory oaks were described in relation to past treatment. In the 1950's and 1960's researchers and ecologists began to quantify oak reproduction under various stand conditions on different sites. Mostly they found lots of understory oaks, but there were exceptions. Researchers thought these exceptions might be important and started to look more carefully at the response of oaks to harvest cutting. Even-aged cuttings quickly showed that on good oak sites without substantial numbers of vigorous advance oak the stands of the future would be quite different. The new stands generally contained less oak. At the same time observers noted that oak types were changing in some areas. More recently, comparisons of repeat forest surveys show a decline of oak types in some states. Increased prices for oak timber suggest that accelerated harvesting is adding to the ecological changes taking place.

We find ourselves with a growing knowledge about oak ecology and silviculture but without a convincing history of being able to prescribe with certainty ways to increase the amount of oak in new stands. Considering the tremendous value of oak forests there is an urgency to improve oak management and to give high priority to long-term research.

INTRODUCTION

Is oak regeneration really a problem? Experts believe that on many sites now occupied by oak, regeneration will become increasingly difficult. How can that be? Oaks are the most prevalent forest types in the United States and dominate much of the East's landscape. Volume growth exceeds commercial removals. It is even more confusing to remember that the present stands were born out of very harsh efforts to either convert forest lands to agriculture through fire and grazing or to mine them of timber with little or no concern for future crops. But it was these very treatments plus the loss of chestnut (*Castanea dentata*) in the Appalachian region that favored oak. Some recommended practices of the last 50 years favor other species at the expense of oak, especially on moist sites where oak quality is best. Paradoxically, we find oak on some of the areas we thought were mismanaged in the past. I believe there is a pressing need for practical alternatives to create conditions to favor oaks on the right sites without detriment to the land or other forest resources.

The very physiologic and genetic characteristics that make oak difficult to establish are the traits that have sustained it through centuries of insults. We have been too impatient in dealing with oak, but there is emerging a better understanding of oak culture. At the same time forest managers have joined users and researchers in common concerns about the future of the oak resource. To understand the complexities of oak regeneration, the status of current prescriptions, and the best direction for future research and development, the Symposium organizers decided to look at the past as prologue for this conference. I have drawn on selected literature along with my own recollections. Consequently, this paper is a collage of facts and personal experience.

To the first farmers of Europe thousands of years ago oaks and other trees were the enemy, something to be girdled with stone axes and burned to make way for crops and a better way of life. In contrast, native Americans living in eastern forests did not rely as much on agriculture and clearing. Their biggest impact on the oak forests related to fire they used or caused. In Europe, by Roman times, oak coppice management regimes developed to improve wood supplies. By the Middle Ages concerns about oak forests led to the French forest ordinances in the 13th Century that mandated practices to establish oak seedlings (Thirgood 1971). Have the French known for hundreds of years what we have been "discovering" over the past 30 or 40 years? Probably, but remember the first American foresters were European-trained and undoubtedly were familiar with oak practices and problems in France, Germany, and Great Britain. Oak was an early export of the American colonies because it was becoming scarce and expensive in Great Britain.

Early American textbooks reflected European silvicultural systems including shelterwoods and coppice. But, there were few references to oak management problems in American forest literature until after the 1930's. There are a number of plausible reasons for this lack of concern: (1) Historically much of the hardwood forest was an unwanted barrier to agricultural development; (2) After several hundred years of harsh treatment and neglect oak trees were still plentiful and there were no serious timber supply problems; (3) Protection and re-establishment were the primary early forestry concerns; and (4) The very practices of indiscriminate burning and overcutting that fostered the forest conservation movement favored oak. It was not so much that we ignored oak regeneration problems in the United States; we are following historical precedence of abundance. We wait to respond to a problem that has emerged over a long time until it has the potential to reduce future supplies. Considering the ecological, economic, and social forces involved we must realistically expect a decline in the oak forest types. However, it is certainly not "too late" to develop and extend the necessary technology to maintain healthy and useful stands throughout the range of oak.

CURRENT CONCERNS NOT NEW

Specific concerns for oak regeneration in the United States go back at least to the early 1800's. Perhaps the first government sponsored forest research in this country was to plant and tend live oak (*Quercus virginiana*) on public land in Florida (Hough 1878). At that time there was great concern about adequate supplies of oak timber for shipbuilding.

Early forestry authors Leffelman, Hawley, and Korstian recognized the kinds and importance of advance oak regeneration (Leffelman and Hawley 1925, Korstian 1927, Hawley 1946). Hawley's 5th edition text, *Practice of Silviculture*, described a successful 1902 shelterwood cutting in Connecticut that favored oak; so there must have been a shortage of advance oak in that stand. Hawley's first edition was printed in 1921 and likely followed European practice. Smith (1962) made a good review of oak regeneration shelterwoods in his silviculture textbook. He also suggested that the term shelterwood is better than the term clearcutting when advance reproduction is involved. A "one-cut" shelterwood for oak *required* that advance reproduction must be established before the final harvest. This excellent perspective is still the conventional wisdom for extensive management.

Liming and Johnson (1944) described oak reproduction in the Missouri Ozarks in 1933 when fire protection started on the new National Forests. Reproduction appeared to be sparse and in poor condition. But within a few years sprout stands emerged from existing roots. Seedling numbers also increased. The authors predicted that with time and protection the forests would improve. And so they have. The change has been dramatic even since 1949 when I first worked under Franklin Liming. As the Ozark forests grew so did the concerns that the next generation of forest stands might be different. A similar "sudden" appearance of oak advance regeneration took place in the late 1800's in southern Wisconsin with the cessation of wildfire as described by Curtis (1959). Crow (1988) provides an excellent historical review and bibliography on oak forests and savannas before European settlement. He cites numerous authors to show how fire and logging favored oak in many parts of the East. In the 1950's Scholz, Arend, Johnson, and others worked on oak regeneration problems as they developed in southern Wisconsin and adjacent Lake States areas.

Information was also accumulating in the Central States. Ecologists Potsger and Friesner (1934) compared a virgin southwestern Indiana oak-hickory forest with adjacent areas cut in the late 1800's and found succession to be a return to oak-hickory and not beech-maple. But from the species lists it is obvious that the sites were dry. Kuenzel and McGuire (1942) reported on clearcut plots in southern Indiana following a bumper crop of chestnut oak (*Q. prinus*) seed. Ten years later 97 percent of the new stand was from stump sprouts. This important information probably did not cause much of a stir among managers but it was picked up by researchers. Illinois plots clearcut in 1935 had good oak 27 years later due to desirable advance reproduction (Bey 1964). In the late 1940's Leon Minckler began a series of compartment studies on the Kaskaskia Experimental Forest in Illinois and showed how oak, especially white oak (*Q. alba*), grew and developed in group selection openings (Minckler 1989).

Studies of oak seed production in North Carolina and Georgia (Downs and McQuilken 1944) also showed the importance of advance reproduction in that area. They suggested shelterwoods were best to regenerate oaks and thought that small group selection openings might also work. By 1958 Merz and Boyce showed that in southeast Ohio the amount of oak in the new stands was directly related to the amount of reproduction established before cutting. In the mid-fifties Ivan Sander and I remeasured plots on the Berea College Forest in Kentucky. The plots were cut in 1923 by the old Appalachian Experiment Station. Sugar maple (*Acer saccharum*) dominated the understory but red oak (*Q. rubra*) dominated the overstory. In 1923 sugar maple was assumed to be a good species for these relatively thin soils. But the more than 30 years growth on these plots showed that red oak was a much better crop than sugar maple in both quality and volume growth (Sander and Williamson 1957). These results made an early impression on me because a maple understory was developing under many mixed oak stands in the Midwest as fire control took hold.

Also, in the mid-fifties I made my first visit to West Virginia and was surprised to hear complaints about "too much" yellow-poplar (*Liriodendron tulipifera*) showing up in the forest landscape even though yellow-poplar is an excellent species. The concerns were about future oak timber and mast supplies. Then, as clearcutting became more prevalent we began to see more yellow-poplar along with red maple (*A. rubrum*). Later, Beck (1988) gave an excellent synthesis and forecast for continued increases of yellow-poplar and other fast growing species at the expense of oaks unless special efforts are made to favor oak establishment and early growth.

In a classic West Virginia study Carvell and Tryon (1961) stated: "The deficiency of oak regeneration beneath mature oak stands is of grave concern to the forest manager since oak regeneration is virtually impossible to obtain quickly." They too found that the composition of the new stand depended largely on the composition of the understory before harvest. However, they counted more oak seedlings than expected in a survey of 59 areas in eight counties. The greater the past disturbance from fire, logging, and grazing, the more oak they found.

Studies in West Virginia (Weitzman and Trimble 1957, Carvell and Tryon 1961) and from other locations showed that moist sites are more difficult to regenerate to oak than are dry sites. The basic problem on moist sites including bottomlands is understory competition.

In 1960 the Division of Forest Management Research of the old Central States Forest Experiment Station under A.G. Chapman prepared a comprehensive problem analysis, *Guidelines for Forest Management Research in the Central Hardwood Region.* It was prepared by committees and represented the conventional wisdom, but not necessarily agreement, of a diverse group of hardwood researchers. It was never published. Some of the conclusions related to oaks and cutting practices 32 years ago were: (1) Reproduction follows all kinds of harvests; (2) Even-age silviculture was better for central hardwoods than selection silviculture; (3) Nearly all clearcutting trials had adequate oak; (4) There was strong evidence that oak consistently followed partial cutting; (5) Major objections to clearcutting related to concerns about sprout stand quality and increased competition of undesirable species; and (6) The quality and importance of advance reproduction was in a state of confusion because of insufficient data. When this analysis was written in the early 1960's there were a large number of active Forest Service oak silviculture studies. Many were new and inconclusive. Highest priority for new research was to find out how to ensure adequate, vigorous regeneration for upland oak. A few years later Forest Service oak research in

Ohio, Kentucky, and Indiana was discontinued. Later the same fate befell most silvicultural research in Illinois and Iowa.

Natural hardwood regeneration research dating from the 1950's was summarized by Sander and Clark (1971). More than 200 cutting plots in Ohio, Kentucky, Indiana, and Illinois were analyzed. This publication provided quantitative data for some of the tenets of central hardwood regeneration at that time. Cutting method had little effect on the amount of regeneration except for yellow-poplar; very few oaks were established after the cuts. The importance of advance oak was stressed, but there were no specific concerns in the text about a lack of advance oaks. However, the statistical tables showed that the Indiana plots—all in one location on the Hoosier National Forest—had a lot fewer advance oak than in other states.

In the late 1960's and early 1970's interests in oak regeneration and management grew as the controversy over harvest cutting methods developed. The forestry community responded to this interest by organizing the first Oak Symposium in 1971 at Morgantown, West Virginia. This followed a special session on hardwood silviculture at the 1968 Society of American Foresters Convention in Philadelphia. I gave papers on regeneration at both meetings at the height of my "oak missionary days" (Clark 1970 and Clark and Watt 1971). Although no longer a research doer, I was part of the movement to get more research results into practice. At the 1971 Oak Symposium, Richard Watt and I synthesized our regeneration recommendations from the work of several researchers including our own. We stated that most maturing stands had enough advance oak but some did not. We had no data on the importance of this problem. Our synthesis has held up fairly well. Since then a number of technical issues are now better resolved through continuing research and new information. Yet, in those 20 years since the first Symposium, progress and proof seem slow. *It is the nature of oak.*

SOLVING THE PROBLEMS

Many attempts have been made to plant oaks but successful plantations were rare in the past. Midwest forest tree nurseries have grown and shipped oaks since the 1930's. I personally checked a number of old oak planting sites from the records of the Hoosier National Forest; all sites were old fields, all were failures. In the late 1950's Bob Williams and I included oaks in our hardwood nursery practices and planting research in Indiana. Most of our time was spent on black walnut (*Juglans nigra*). We had good success with walnut, some encouraging results with red oak, and poor results with white oak. We were convinced that site selection, stock quality, and competition control were very important for all hardwoods. Following a series of studies started in the 1960's, Johnson (1985) reported some success with oak underplanting in Missouri. More recent oak planting studies have produced positive results on upland sites in the Central and Lake States, the Mid-South, and the Northeast. There are also reports of successful planting on bottomland sites. The goal is to substitute planted oak on problem sites without natural oak regeneration. The outlook for operational planting is now much better, but risks and costs are still high.

Early researchers recommended that advance oak must be big or vigorous enough to compete in the new stands, but specifics on size were not available until the 1970's. Perhaps the classic study of the response of different kinds and sizes of oak regeneration was on the Kaskaskia Experimental Forest. Sander (1972) concluded from 12-year data that only advance oak 4.5 ft. or taller could compete in the new stand. He suggested it would be better to have 6-to-8 ft. regeneration before final cutting. Some of the more esoteric results of that research deserve careful restudy by serious oak researchers and managers. Only the regeneration types with older, well-developed root systems grew to the recommended height during 12 years in partial cut stands with only 29 percent overstory stocking. This is a bit chilling when considering shelterwood schedules in areas with scarce advance oak.

Sander, Johnson, and Watt (1976) developed specific guidelines to evaluate the adequacy of advance oak. This work continues to be refined but applies mainly to Missouri. Carvell (1979) did some original work on the importance of recognizing not only the size but also the vigor of advance oak. He too stressed the importance of adequate advance oak based on his earlier work and suggested how to make preharvest assessments (Carvell 1988). Loftis (1988) used an approach similar to Sander and associates to determine the oak regeneration potential for areas in the Appalachians.

Most authors stressed that it is essential to have large numbers of well-developed oaks in the understory prior to the final harvest. In sharp contrast, Johnson and others (1989) reported on a mesic site clearcut in southwestern Wisconsin that was successfully reproduced with new red oak seedlings. In this general area oak is being replaced through successional pressure of more tolerant species. In this case study, competition was greatly reduced by treating the understory with herbicides 2 successive years, and then removing the overstory after a good seedfall. The authors also cited examples of both success and failures with fewer and smaller advance red oaks than usually recommended. Johnson and others (1989) suggested that competition control with herbicides may substitute for the long regeneration period suggested in the literature. But they caution that a shelterwood is safer than a clearcut and that understory treatments may vary among ecosystems. Understory control has been suggested for many years as a potential solution to competition problems, but we still need specific prescriptions supported by practical demonstrations for a variety of problem areas.

RECENT HISTORY— PROBLEMS GROW

In 23 selectively cut private woodlands in southern Indiana, 95 percent of the openings created were too small to stimulate advance oak growth (Callahan and Fischer 1982). Oak was a substantial overstory component in most of the woodlands studied, but oak reproduction more than 6 ft. tall were found on only 2.4 percent of the transects. While the 23 areas appeared to be productive, the authors found them to be seriously understocked with desirable species. Callahan and Fisher concluded: "The present prospects appear dim that many oak trees will grow in future stands on upland hardwood sites."

Responding to concerns about cutting practices on the Hoosier National Forest, George and Fischer (1989) reported on an intensive regeneration survey on five 17-year-old clearcuts in southern Indiana. Their data showed that the new stands have more yellow-poplar and less oak than the stands harvested. They point out that long-term development trends remain unanswered. One important question is will the more mesic species fade with time and drought as reported by Hilt (1985) in southeast Ohio? Interestingly, the yellow-poplar/oak trends in a large number of commercial clearcuts discussed by George and Fischer (1989) were consistent with data found in Sander's and Clark's 1971 report for southern Indiana plots and the increased incidence of yellow-poplar elsewhere.

With the advent of fire and grazing protection, oak stands in Iowa and Missouri are in various stages of conversion to sugar maple and other hardwoods, according to Countryman and Miller (1989). Recently, McGee (1989) found that an old stand of mixed hardwood with a substantial oak component is suddenly experiencing rapid overstory decline. In spite of the fact that this middle Tennessee old-growth on an excellent site had survived for decades, there is little chance that oak will be in the new stand under natural succession. Some eastern stands with severe gypsy moth mortality are not returning to oak but are now occupied by such low-value species as red maple that dominated the understory when the oak overstory declined. The potential loss of the oak type through gypsy moth is devastating.

Tracing the historical development of 46 red oak stands in northern Wisconsin provides strong evidence that these stands replaced other species and associations following past heavy cuts and fire (Nowacki, Abrams, and Lorimer 1990). The authors suggest that northern red oak in the study area may be limited to one generation and will be replaced by the tolerant red and sugar maples on all but the driest sites. The authors provide a brief overview of the mostly 1980's ecological literature to support the growing belief "that a high proportion of stands are on the threshold of a dramatic change in structure and composition." They too suggest that dry sites may be an exception to the ecological "instability" of eastern forest oak stands. These are strong and sobering opinions shared by a growing number of ecologists and foresters. Questions of oak stand dynamics have been around for a long time but evidence accumulates with the time it takes for ecological trends to manifest.

Crow (1991) concludes that in the Upper Midwest landscapes "future forests will differ in composition and structure from past and present forests." Crow (1988) also refers to the present abundance of oak in eastern forests as "an artifact of disturbance regimes that are no longer common." Spencer and Kingsley (1991) give us definitive insight to oak resource problems from the perspective of forest inventory type changes. Their analysis covered the seven-state Upper Midwest from Indiana to Minnesota. They compared the latest oak forest inventories with previous inventories. The average time between inventories was 15 years. During that "average" period oak types *lost 6.5 percent in area* but increased in total volume. Four of the seven states decreased in oak area. The increased area in the other three states was due primarily to a classification anomaly of wooded pastures shifting to timberland between inventories. Indiana had the biggest oak loss, 36 percent for the 19 years between surveys. That was an average annual conversion of 1.9 percent of oak types into the more mesic maple-beech type. This report also shows that only 17 percent of the oak types are in seedling-sapling stands, and is further proof that many oak stands are not replacing themselves. Spencer and Kingsley suggest that red oak is being overcut in Illinois and Indiana. Research economists in the Lake States found that the value of red oak lumber and logs has been increasing 6 to 8 percent a year above the inflation rate since the 1970's (North Central Forest Experiment Station 1991). Stumpage prices for both domestic and export logs are up dramatically, suggesting a growing scarcity of "available" high quality trees. History repeats itself, only this time it is not a shortage of oak for shipbuilding and fuel.

Nyland (1992) has expressed strong concerns about potentially serious consequences of selective and diameter limit cuts in eastern hardwoods. He suggests that exploitive harvests following the development of export markets "portends a long-term conversion in composition that promises lower market values in the future, especially among oak communities." Ralph Nyland, one of the countries leading hardwood silviculturists, calls on practicing foresters to be more aggressive in promoting good forestry to stop the second great exploitation of the eastern forests.

Spencer and Kingsley's (1991) analysis of what is happening in the Upper Midwest is a dramatic picture of recent "historical" trends in oak ecology. Considering the Indiana data, the situation is cause for serious concern for those who want to maintain oak on good sites. Are we really witnessing successional changes taking place at a rapid rate? Yes, *but* it is not all "natural" succession. Selectively harvesting oak is probably most responsible for type conversion changes from one inventory to the next. Inventory forest types relate to the overstory, so removing the oak and leaving most of the other species automatically changes the type. What is left, the residual type, does not bode well for regenerating a new oak stand. Other harvest methods, such as clearcutting without vigorous advance oak regeneration, can also result in type conversion.

AND WHAT OF THE FUTURE?

Practicing field foresters in the Northeast ranked oak regeneration guidelines as the eighth most important research need out of 46 research problems (Broderick and others 1991). The authors stressed that the 660 respondents were well qualified to give an accurate picture of research needs. Yet the authors point out that "the literature does not lack for such information" and cite work done in the Central States and Missouri. They suggest that foresters may be "unaware of existing research or they are not satisfied with it" and that there may be problems in technology transfer. All of the above is true. But we need to understand that existing oak regeneration guides are based on data from limited areas and should only be extended with caution, validation, and perhaps additional research and testing to account for regional ecological differences and past treatments. In my experience, the call for more research is often based on an inadequate knowledge of information that already exists. But there are problems with the transfer of oak technology, and my definition of oak technology includes information for understanding oak ecology and ecosystems with oak. Too few managers and researchers are well founded in oak ecology; I include my own generation as part of the problem. Oak silviculture and management is far too complex to relegate to "standard" prescriptions.

Just as the present stands changed over time, so will the next rotation change under different treatments and environmental influences. Unfortunately, a lot of past long-term oak research has been discontinued due to costs and changing priorities. With new technology to handle data it is not too late to salvage some of this work, especially on areas with good understory records. A new look at some of the older studies may answer a very important question: Will oak outlast some of the more mesic species? Recently there has been a call for more financial support for long-term, basic ecological research. What could be more "basic" than understanding what is happening to the largest forest types in the United States surrounding a majority of the country's population? Like forester-turned-pathologist-turned Nobel Peace Prize winner, Norman Borlaug, I believe: "Our research must be good, but it must be good for something."

PUTTING HISTORY TO WORK

In the past 10 years there have been at least six major conferences, from Pennsylvania to Minnesota and now Tennessee, that have addressed oak problems and solutions. From an historical perspective this unprecedented interest and concern for oak is both encouraging and further evidence that there are serious management problems over a broad area. Published prescriptions, guides, and texts are now more definitive but with room for improvement as new information emerges. The vast extent of the oak forests with their inherent and acquired variations makes them very difficult to know and manage. With that difficulty comes the challenge and excitement of working with a resource that has provided for the needs of both ancient and modern mankind from food to esthetics.

There is no easy way to summarize the history of oak regeneration problems except to say that it is lengthy, complex, paradoxical, and often perplexing. But do not forget the first canon of oak management, *regeneration is a process, not an event.* I commend to both researchers and managers a reading of some of the older literature. It is educational, sobering, and sometimes humbling. New and helpful interpretations are possible as pieces fit together and we learn the value of the knowledge base we inherited, and appreciate those who bequeathed it.

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Causes of the Oak Regeneration Problem

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ABSTRACT

Historical records indicate that oak species dominated much of the central hardwood forest at the time of settlement. However, many oak stands harvested in the past 40 years on average or good sites are now dominated to various degrees by other hardwood species. Several possible causes are discussed, including acorn predation, climatic change, damage to seedlings by insects and deer, and excessive competition resulting from decreased fire frequency. A number of these factors appear capable of reducing the success of oak regeneration or causing nearly complete failures. However, mature oak stands usually have several hundred to several thousand oak seedlings per acre present in the understory. The crux of the problem often appears to be the failure of these seedlings to survive and increase in vigor, even when released from competition. Slow juvenile growth occurs even where deer browsing is uncommon and appears to be an inherent trait of northern red oak and white oak on mesic and dry-mesic sites. Experimental evidence shows that the dense understory of shade-tolerant species on mesic sites is a major limiting factor to adequate oak seedling development, and that seedling development is markedly improved if the understory is removed. Historical evidence suggests that many of our existing oak stands on mesic sites either developed after fire or were periodically subjected to fire and other disturbances removing understory and subcanopy trees. Historical evidence on changes in fire frequency is reviewed, and problems with the fire hypothesis are discussed.

INTRODUCTION

If a panel of practicing foresters and researchers were asked to "round up the usual suspects" implicated in causing oak regeneration failures, it would probably not take long to produce a hefty list. Erratic seed production, predation of acorns by insects, rodents, and deer, defoliation and browsing of established seedlings by animals, and intense competition with other vegetation have all been implicated. Foresters also wonder about recent changes in the environment. Fires and grazing are no longer a dominant force, woodlands are fragmented in many areas, chestnut (*Castanea dentata*) is no longer a major component of the canopy, predator control has altered animal populations, new insects have been introduced from other continents, and the climate may be changing.

Are all these factors having a major impact on oak regeneration? It may be useful to make a distinction between an "aggravating factor" and a "limiting factor." An aggravating factor may reduce the frequency of seedling establishment or the rate of seedling growth, but is not ordinarily capable by itself of causing complete regeneration failures. A limiting factor, on the other hand, can cause nearly complete regeneration failures even if no other aggravating factors are present. It is possible, of course, for certain factors to be merely aggravating at some times or places and limiting in others.

Because of this variability, we need to view "the oak regeneration problem" as having both local and regional aspects. Oaks, like other species, can have local regeneration failures in response to chance factors such as seed crop failure or locally intense browsing. But it is the relatively sudden and repeated regeneration failures over widely separated areas that have been the cause of recent concern. Questions naturally arise: Is there a common underlying cause behind the regional problem? Is the regional problem caused by the cumulative impact of a host of aggravating factors or primarily by one or more limiting factors?

The ideal solution to resolving these questions would be to conduct controlled experiments that would simultaneously evaluate a number of factors and would be replicated in several geographical areas. One study underway in the Northeast may, in a few years, help sort out the importance of various factors in that region (Galford and others 1991). In the meantime, a review of causal factors over the central hardwood region must rely on a combination of limited experimental evidence, observational data or empirical correlations, and historical evidence.

Explaining the Facts of the Case

Faced with a host of possible causal factors and limited evidence, a reasonable place to start is to list a number of facts concerning the oak regeneration problem that must be explained by any convincing hypothesis. The following list includes some of the major considerations:

(1) Oaks have dominated much of the central hardwood region for over 6,000 years. At the end of the glacial episode, much of central hardwood region was occupied by a boreal forest of spruce and pine. About 6,000-9,000 years ago, this boreal forest was replaced by an oak-pine-mixed hardwood forest, which has retained dominance ever since (Craig 1969, Watts 1979, Delcourt and Delcourt 1985). This evidence from the pollen record is supported by independent historical evidence on the presettlement forest (ca. 1600-1850) from early travelers and government land survey records. For example, species of oaks comprised 40-80 percent of the witness trees in sizable areas of New Jersey, Pennsylvania, Virginia, Kentucky, and Illinois (Spurr 1951, Russell 1981, Leitner and Jackson 1981, Bryant and Martin 1988, Abrams and Downs 1990). Thus, while disturbances that accompanied European settlement may have increased oak dominance in some places, particularly at the margins of its range (Whitney 1987, Nowacki and others 1990), oak was already dominant over large sections of the landscape and maintained by natural regeneration long before European settlement.

(2) Oak regeneration failures appear to have been a widespread problem only in the last 50 years or so. This trend is seen most clearly by the fact that oak stands on mesic sites clearcut after about 1930 are now frequently dominated by species such as maples (*Acer rubrum* and *A. saccharum*), yellow-poplar (*Liriodendron tulipifera*), hickories (*Carya* spp.), and black cherry (*Prunus serotina*), while stands

originating prior to 1930 on similar sites are usually dominated by oaks (Johnson 1976, Heiligmann and others 1985, Beck and Hooper 1986, Hix and Lorimer 1991, Abrams and Nowacki 1992).

(3) Oak regeneration is often successful on the drier or below-average sites. The site specific nature of oak regeneration problems has been known for some time (e.g., Weitzman and Trimble 1957). Until more detailed habitat classifications are available, site index can serve as a rough guide. In many areas, sites with an oak SI of 60 ft. or less are likely to support stable, self-perpetuating oak forests, while those with SI >60 are likely to convert wholly or in part to more mesic species (Hilt 1985, Hill 1987, Loftis 1988b, Zaldivar-Garcia and Tew 1991). Stable oak forests usually have a sizable component of the more xerophytic species, such as chestnut oak (*Quercus prinus*) and black oak (*Q. velutina*), whereas the stands most susceptible to regeneration failures usually occur on the more mesic sites dominated by northern red oak (*Q. rubra*) and white oak (*Q. alba*). A convincing hypothesis should be able to explain this clear habitat-related variability. For example, if insects or deer are proposed as limiting factors, is there evidence that animal damage is consistently less serious on SI 60 lands than on SI 70?

(4) The oak regeneration problem is geographically widespread. Pinpointing the geographical extent of oak regeneration failures is difficult because regeneration surveys taken in the first few years after harvest can be misleading (Bey 1964, Oliver 1978). Whether or not oak will be a major part of the canopy can only be determined with reasonable confidence after the forest has entered the "pole stage" of development, when the forest has developed a closed canopy and stratified into crown classes (e.g., after age 25). Using these criteria, unintended conversions of oak forests to other species have been documented most clearly on average and good sites in the Ridge and Valley section of central Pennsylvania (Abrams and Nowacki 1992), cove forests of the southern Appalachian Mountains (Beck and Hooper 1986), upland sites in southern Michigan (Gammon and others 1960), and upland sites of southwestern Wisconsin (Johnson 1976, Hix and Lorimer 1991). A similar study on an average site in southeastern Ohio suggests a significant reduction in the oak component (Heiligmann and others 1985). Succession of oak forests to sugar maple and other shade-tolerant species is less certain but still likely to occur on mesic sites examined in eastern Tennessee, central Indiana, southern Illinois, and the River Hills area of Missouri (McGee 1984, Parker and others 1985, Schlesinger 1989, Pallardy and others 1988).

From this evidence it is clear that oak regeneration problems are not confined to northern states at the margin of the range, which might otherwise be most affected by climatic change. Also, problems are occurring far outside the original range of American chestnut, as well as in areas such as the southern Appalachian Mountains where the forest is not highly fragmented.

REVIEW OF EVIDENCE ON POSSIBLE CAUSES

Because successful oak regeneration usually depends on the existence of seedlings in the understory before harvest (Sander 1972, McQuilkin 1975), poor seed crops and high rates of consumption by animals can have significant impacts on the ability of oaks to compete with other species. Unfavorable weather and insect damage can both lead to poor acorn crops (Cecich 1991). Most of the eastern

Limited Production and Heavy Consumption of Acorns

upland oak species, however, have good seed crops at intervals of 3-5 years (Burns and Honkala 1990). Intervals between good seed years in white oak may be longer (Rogers 1990), and local factors might occasionally lead to regeneration failures from this cause. Smith (1993) has reported that average intervals between good acorn crops may be as long as 10 years in the central Appalachians.

Destruction of acorns by insects, rodents, and deer is probably a more important factor in most areas; a loss of 90 percent of the current crop is typical (Arend and Scholz 1969, Marquis and others 1976, Galford and others 1991). In a recent study in Pennsylvania, rodents removed virtually every unprotected acorn on the ground surface and 78 percent of the buried acorns. Insects destroyed 63 percent of the surface acorns protected from rodents (Galford and others 1991).

Marquis and others (1976) found that acorn production and the activity of insects and rodents varied greatly in different stands for unknown reasons. Compared to a stand with abundant advance regeneration, a stand with few oak seedlings (96 per acre) not only produced fewer acorns, but twice as many were damaged by insects, and pilferage by rodents was three times as high.

Such evidence suggests that destruction of acorns by animals can potentially be limiting factors in some locations. Whether it is a major cause of the regional problem is not as clear. Thorn and Tzilkowski (1991) point out that by burying acorns in well-distributed caches, small mammals may actually facilitate seedling germination. In that study, small mammal activity resulted in 28,000 well-distributed caches per acre. Thus, an acorn that disappears from a seed trap should not necessarily be considered "destroyed." More importantly, a review of many studies in the central hardwood region shows that most mature stands have several hundred to several thousand oak seedlings per acre at any one time (Carvell and Tryon 1961, Nowacki and Abrams 1992, Merritt and Pope 1991). Thus, seedling germination is not a limiting factor in many areas. Beck and Hooper (1986) documented an oak regeneration failure that occurred even though more than 5,000 oak seedlings per acre were present at the time of overstory removal.

Damage to Seedlings by Animals

Although large numbers of oak seedlings may become established after bumper acorn crops, mortality rates of young seedlings are high, especially on mesic sites (Johnson 1985). A newly established cohort of seedlings in a mature stand on a good site in the Southern Appalachians had a 10-year survival rate of 10 percent, with negligible growth of the survivors (Loftis 1988a). Could repeated defoliation and other animal damage be a factor in causing high mortality and slow growth?

Evidence on seedling damage by insects is very fragmentary. An insect with a potentially serious impact on oak seedlings is the Asiatic oak weevil (*Cyrtepistomus castaneus*) because larvae feed on fine root hairs and adults feed on leaves (Triplehorn 1955, Roling 1979). The weevil, introduced from Japan and first recorded in New Jersey in 1933, is now distributed in most of the eastern states as far west as Missouri and Kansas. In Missouri, the weevil has a strong preference for oak and apparently has little impact on other hardwoods (Ferguson 1987). Linit and others (1986) reported 46 insect species, including the Asiatic oak weevil, associated with planted oak seedlings in Missouri. Leaf area losses averaged about 22 percent over a season. The impact on growth was not measured, but was not necessarily considered to be severe.

In addition to obtaining more evidence on the impact of low to moderate defoliation on growth and vigor, more evidence is needed on insect activity across habitat types. The introduction of the Asiatic oak weevil in about 1930 did coincide with the start of major oak regeneration failures, but for that to be considered a principal limiting factor, evidence would probably be needed that weevil activity is concentrated on mesic sites where most oak regeneration failures occur.

The potential for deer browsing to block the development of competitive oak advance regeneration is better documented than insect damage. The deer population on the Allegheny Plateau in Pennsylvania (often more than 30 per square mile) is sufficient to create open, park-like stands with little undergrowth. Where deer populations are high, browsing can occur on oak seedlings that are as short as 15 in. high (Galford and others 1991). Sometimes there is so little advance regeneration of hardwoods that clearcuts revert to grass and scattered shrubs (Marquis 1974).

Published evidence on the effects of deer browsing on oak is very limited outside of Pennsylvania. Similarly severe effects have been documented elsewhere, but the problem is often quite localized. High deer populations (34-59 per square mile) in a game preserve in Massachusetts have created savanna-like conditions, but in the surrounding region the deer average only 3-8 per square mile and browsing is limited (Healy and Lyons 1987). The intensity of deer browsing appears to vary greatly from place to place. Four underplanting trials of northern red oak in southern Wisconsin have shown little browsing in two counties with average deer populations of 18 per square mile (Pubanz and Lorimer 1992), but destructive levels of browsing in counties with average deer densities of 25-35 per square mile (Pubanz and Lorimer, personal observations). In the mountains of West Virginia, moderate-sized clearcuts (e.g., 20 acres) develop so much vegetation that the ability of deer to modify the outcome is limited (H. C. Smith, personal communication). While deer browsing was observed on oak seedlings in a southern Appalachian cove stand, and may have contributed to the slow growth rate (Beck 1970), the problem of slow growth persisted long after the deer density had greatly diminished (D. E. Beck, personal communication).

Deer browsing is clearly a limiting factor for oak regeneration in some places, and the substantial growth of deer populations that occurred in many areas around the 1930's does coincide with the beginning of widespread oak problems. However, the occurrence of oak regeneration failures in places where deer are not especially numerous makes a number of researchers feel that deer are generally more of an aggravating factor than a primary limiting factor. We need more evidence, however, on the effects of moderate deer browsing on growth rates, especially where deer may be browsing oak in preference to other species (George and others 1991). Furthermore, the deer problem seems to be getting progressively worse. Deer populations in the lower Midwest were historically low (USDA Forest Service 1970) but appear to have increased substantially in recent years (e.g., Ishmael 1990). As one forester in Indiana remarked, complaints about deer damage are becoming more numerous, and establishing a hardwood plantation is often like "setting the table for deer."

Excessive Shade and Competition

Another explanation for the slow growth and high mortality of understory oak seedlings besides insect and deer damage is the detrimental effects of dense understory vegetation. Northern red oak and white oak both appear to have a growth strategy in which photosynthate is diverted to root growth at the expense of shoot development (Crow 1988, Dickson 1991). Seedlings may, therefore, develop a stout taproot and persist for many years despite repeated shoot dieback (Merz and Boyce 1956). When an opening occurs, such "seedling sprouts" are often capable of rapid growth (Bey 1964, Sander 1972).

This strategy is effective on dry-mesic or xeric sites where moisture may be limiting and a moderate amount of light reaches the forest floor, but it is a poor strategy on mesic sites where light levels are much lower (Dickson 1991). Shade-tolerant species such as maples have an important advantage over oaks because they can make significant height growth under a closed canopy, steadily increasing in both size and number until a nearly continuous subcanopy or a multi-storied layer of vegetation develops (Lorimer 1984). These added layers of foliage beneath a closed upper canopy intercept so much light that often less than 1 percent of full sunlight reaches the seedling layer (Hanson 1986, Pubanz and Lorimer 1992). Hanson (1986) demonstrated a negative carbon balance for northern red oak seedlings growing under a heavy canopy. As a result, seedlings often die once acorn reserves are exhausted, and even among the survivors a vigorous root system doesn't ordinarily develop (Crow 1988).

The ability to persist under dense shade appears to vary among oak species. White oak and chestnut oak, for example, are often considered to be moderately shade-tolerant (McGee 1981, McQuilkin 1990). However, the shade tolerance of oaks is markedly less than for many of its mesic competitors. The average 5-year mortality rate for large, overtopped saplings in a dry-mesic stand in southern New York was 45 percent for northern red oak and 26 percent for chestnut oak, but only 11 percent for red maple (Lorimer 1981). On a dry-mesic site in central Massachusetts, overtopped red oak had a 19-year mortality rate of 90 percent compared to only 16 percent for red maple (Lorimer 1983).

A recent field experiment in southwestern Wisconsin showed that even vigorous, nursery-grown northern red oak seedlings are mostly unable to survive when underplanted in mature, undisturbed oak forests on mesic and dry-mesic sites. After 5 years, over 70 percent of the planted seedlings had died on both sites. However, in plots on the same sites where the understory layer was removed, planted seedlings not only had 93 percent survival, but seedlings doubled in height and had an average of 35 leaves after 5 years (figures 1 and 2).

Such evidence suggests that the presence of a dense understory of shade-tolerant species is often sufficient to prevent the development of vigorous oak advance regeneration, whether or not other limiting or aggravating factors are present. The small oak seedlings typically present on average and good sites grow very slowly, and usually seem incapable of rapid growth even if the overstory is removed (Beck 1970, McQuilkin 1975, Sander 1972, Beck and Hooper 1986). A typical harvest operation on mesic sites creates a situation in which scattered oak seedlings, usually less than a foot tall and capable of growing only a few inches in height per year, must compete with thousands of tall saplings of other species capable of growing 18 to 24 in. in height per year (Beck and Hooper 1986; Hix and Lorimer 1990, 1991). Early spring frosts, which McGee (1986) found especially damaging to oak seedlings that originated beneath a canopy, could place oak seedlings at a further disadvantage.

In contrast to mesic sites, where one cohort of oak seedlings may largely disappear before the next one germinates, drier sites often have oak seedlings that may persist for up to 30-50 years, developing a strong root system and often a tall shoot as well (Liming and Johnston 1944, Sander 1972, Johnson 1991). Even if saplings of shade-tolerant competitors are present on these sites, they may not be numerous enough or vigorous enough to present a serious challenge. Development of vigorous oak seedlings on mesic sites is feasible, but it has only been demonstrated in cases where understory vegetation has been eradicated before or at the time of overstory removal (Johnson and Jacobs 1981, Johnson and others 1989, Lorimer 1989, Loftis 1990, Nowacki and others 1990). In the following section, evidence is reviewed on historical conditions that may have permitted the expansion of oaks onto mesic sites where they ordinarily would not be competitive.

Figure 1—Before (top) and after (bottom) understory removal and light thinning of the canopy on a mesic site dominated by northern red oak in southwestern Wisconsin. These treatments increased natural oak seedling establishment by 400 percent and greatly stimulated the growth and vigor of underplanted oak seedlings (Pubanz and Lorimer 1992).

Figure 2—(Left) Northern red oak seedlings underplanted in an undisturbed mature oak forest in southwestern Wisconsin had 74 percent mortality after only 5 years, and survivors had low vigor and no net height growth. (Right) Seedlings underplanted in stands where the understory was removed (see figure 1, bottom) had 93 percent survival and doubled in size. This experiment illustrated the inability of even vigorous, nursery-grown oak seedlings to survive beneath the shade-tolerant understory of a typical mature forest (Pubanz and Lorimer 1992).

HISTORICAL FACTORS

Origin of Existing Oak Stands

If oak regeneration on mesic sites is so difficult, how did the existing stands originate? Detailed stand records rarely go back as far as 70 or 80 years, but comments by contemporary observers, supplemented by field evidence on stand history, can give us a general idea of stand origins.

The most thorough evidence comes from the Midwest, because it was the last part of the central hardwood region to be settled and has the best records. Many midwestern oak stands occur on sites that supported oak savannas at the time of settlement. These savannas were usually dominated by the more fire-resistant species such as bur oak (*Q. macrocarpa*), white oak, and black oak, and were "covered with trees about as far apart as in a common orchard" (Bayley 1954). Oak savannas are estimated to have covered between 13-32 million acres in eight states (Nuzzo 1986). Based on 19th century land survey records, Curtis (1959) estimated that southern Wisconsin at that time was approximately 45 percent oak savannas, 20 percent prairie and sedge meadow, 25 percent maple and floodplain forest, and 10 percent oak forest. There is little question that these oak savannas were fire-maintained and fire-dependent (Gleason 1913, Muir 1913, Curtis 1959, Grimm 1984). For example, in 1750, Father Vivier wrote that in the Ozark region, "trees are almost as thinly scattered as in our public promenades. This is partly due to the fact that the savages set fire to the prairies toward the end of autumn, when the grass is dry; the fire spreads everywhere and destroys most of the young trees" (Johnson 1992). In Wisconsin, the more fire-sensitive northern red oak was often present only as brushy sprouts or "grubs" among the prairie grasses (Curtis 1959). When the fires ceased, "the grubs grew up into trees, and formed tall thickets so dense that it was difficult to walk through them and every trace of the sunny *openings* vanished" (Muir 1913). Many of the red oak stands being harvested today appear to be the first—and only—generation of closed-canopy oak forest to follow the savannas. Stands harvested in recent decades have been displaced by the shade-tolerant species that quickly developed as an understory beneath the oaks (Johnson 1976, Jokela and Sawtelle 1985, Hix and Lorimer 1991).

Existing oak stands in states farther to the east, in the Piedmont-Appalachian region, originated after 50-100 years of influence by European settlers, and in a number of different ways:

(1) Some of our existing oak stands on mesic sites originated after intense fire and are even-aged (Brown 1960, Ward and Stephens 1989, Nowacki and others 1990).

(2) Some eastern oak stands apparently originated in a manner similar to those in the Midwest, after the cessation of repeated fires. In the southeastern Piedmont, Hammond (1880) noted that "since the discontinuation of spring and autumn fires, [a deer] could not be seen at fifteen paces, because of the thick growth of oak and hickory that has taken over the land." Grazing was also widespread at the time (Greeley and Ashe 1907) and may have had an effect similar to fire.

(3) Probably millions of acres of existing oak forest, both in the Northeast and Southeast, originated as an understory beneath a pine canopy (Hammond 1880, Oosting 1942). In central New England, 65-70 percent of the land had been cleared for agriculture at some point, but much was subsequently abandoned. Much of this land reverted to "old-field" pine. As can be seen today, old field pine stands usually have a relatively sparse understory, but oak saplings 3-15 ft. tall are common. Data gathered by McKinnon and others (1935) in central New England show an average of 578 saplings per acre released after the harvest of old-field pine on good sites, of which 215 were oak. The oaks typically became the dominant species in the subsequent stands (Oosting 1942, Lutz and Cline 1947).

(4) Many oak stands in the mid-Atlantic region appear to have originated after repeated, intensive clearcutting to produce charcoal for the iron and brick industries. Because stem quality was not an important consideration, small stems as well as large could be utilized, and clearcutting was often done at short intervals of 30-40 years (Schnur 1937, Raup 1938, Abrams and Nowacki 1992). Approximately 300 acres of forest had to be cleared each year to supply a single iron furnace (Stout 1933). Fires often followed. All of these factors would have favored vigorous sprouters such as oaks and hickories. The coppice nature of most stands was such a prominent feature of the landscape that Hawley and Hawes (1912) mapped a large area of southern New England, New York, and New Jersey as the "Sprout Hardwoods Region." These historical circumstances are much different from the prevailing situation today, when small trees are in little demand, and both logging and natural blowdown remove only the larger overstory trees and leave the small tree layer largely intact.

Although our existing oak forests on mesic sites have clearly originated in a variety of ways, the common denominator in all of these scenarios is that historical events resulted in a "low competition" environment in which sizable understory trees were either absent, sparse, or periodically eradicated.

Fire Effects on Oak Regeneration

Most oak species have biological traits, such as relatively thick bark and protection against rootkill, that suggest an adaptation to periodic fire. Perhaps the most significant impact of fire is its reduction in the density of shade-tolerant saplings, which as noted above, is probably the most common inhibiting factor in oak regeneration. In a study in central New York, mortality of saplings caused by accidental spring fires ranged from 35 percent in ironwood *(Ostrya virginiana)* to 93 percent in hemlock (*Tsuga canadensis*), but only 12 percent of the oaks and hickories were root-killed (Swan 1970). Others have reported similar selective discrimination of fire against shade-tolerant competitors (Brown 1960, Carvell and Maxey 1969, Kruger 1992). Fire may also result in a major reduction in shrub cover (Nyland and others 1982, Abrams 1988, Reich and others 1990). As a result of this selective reduction of competitors, oaks may increase in relative density even if the absolute density remains unchanged.

Evidence for positive effects of fire on oak seedling establishment, on the other hand, is currently rather inconclusive. Several studies of prescribed burns have shown little or no increase in oak seedling establishment after the burn; in several cases, the fire resulted in a great influx of other species or resprouting of competitors as multiple-stemmed clumps (Sims 1932, Johnson 1974, McGee 1979, Nyland and others 1982, Wendel and Smith 1986, Merritt and Pope 1991). Others have produced evidence that burning can substantially increase oak numbers (Keetch 1944, Carvell and Tryon 1961, Carvell and Maxey 1969, Niering and others 1970, Thor and Nichols 1973, Little 1973).

There may be several reasons for these discrepancies. Many of the studies reporting discouraging results are based on short-term observations (2 years or less) after a single, low-intensity prescribed burn on good sites. If a good acorn crop doesn't occur during this period, a substantial improvement in oak seedling establishment is not likely. A single burn will often not accomplish much, and may even be counterproductive on mesic sites, where it may simply aid the establishment of competing vegetation. A number of researchers have suggested that repeated burning over a period of time may be necessary (Van Lear and Waldrop 1988, Loftis 1990, Johnson 1992). As Komarek (1974) once commented in relation to southern pine: "All too often investigators in the past have expected miraculous results with one light burn after years of fire exclusion." Nearly all of the studies reporting increases in oak seedling establishment involved several burns. Unfortunately, however, most of the reported successes with fire have occurred on dry sites. Clearly we need more evidence on the long-term effects of repeated burns on mesic sites.

The effect of intense wildfire on oak regeneration has received less attention, but it is this type of fire that has produced the most dramatic results on mesic sites. Carvell and Maxey (1969) reported that an October wildfire in a young stand of mixed cove hardwoods in West Virginia increased the number of dominant oaks from 93 to 293 per acre. Fifty-five years after an intense surface fire in a Connecticut mixed hardwood stand, burned sections increased oak and hickory dominance by 240 percent compared to unburned sections (Ward and Stephens 1989). Similar results were reported by Brown (1960) in Rhode Island. In the northern hardwood region, northern red oak has sometimes displaced the hemlock-maple type after intense slash fires (Nowacki and others 1990). In such cases where intensive site preparation or competition control has taken place, surprisingly rapid growth of newly established oak seedlings sometimes occurs that would not be expected under other circumstances (Johnson and others 1989, Lorimer 1989).

Climatic Change

Oaks are usually considered to be favored by relatively warm and dry climates, and paleocologists often use abundant fossil oak pollen as one indicator of this type of climate. Oak regeneration failures could in principle be related to a shift to cooler and moister conditions. This change would probably have an effect of a southward shift in the boundary between northern (beech-maple) and central hardwoods (oak-hickory). In other regions, it might also cause an expansion of mesophytic species onto sites that were once relatively warm and dry, with a corresponding shrinkage of microhabitats that were formerly stable oak sites.

The issue of possible climatic effects needs further study, but several important lines of evidence seem rather inconsistent with the hypothesis that climatic change has been a major causal factor. There is little evidence in the pollen record that a rather dramatic cooling episode known as the "Little Ice Age" (ca. 1400-1850) had any substantial impact on oak dominance (Davis 1958, Watts 1979, Patterson and Backman 1988). Indeed, most early explorers in the Northeast described oak as the dominant forest type. Second, data show that the climate has been warmer (and drier) in recent decades compared to the late 19th and early 20th centuries (Wahl 1968), a trend that should not be favorable for the shade-tolerant competitors. Third, a relatively warm and dry climate does not seem to facilitate oak regeneration on mesic sites or hinder the development of mesic competitors to any noticeable degree. This relationship is apparent from the development of dense understories of sugar maple on mesic sites in southern Illinois, southwestern Wisconsin, and the River Hills section of Missouri, all of which were at or close to the original prairie border (Schlesinger 1989, Pallardy and others 1988, Hix and Lorimer 1991).

Historical Changes in Disturbance Frequency

If a major cause of the regional oak regeneration problem has been the development of dense understories of competing species on mesic and dry-mesic sites, some evidence would be helpful in clarifying whether or not the magnitude of factors inhibiting understory development was sufficient prior to 1930 to account for the existing widespread occurrence of mature oak on mesic sites, and whether these factors have subsequently decreased.

The Post-Settlement Era (1750-1930)

Most or all of the factors involved in the creation of existing oak stands, and discussed in previous sections, were widespread in the post-settlement era. Numerous sources, such as Van der Donck (1656), Kalm (1770), Harris (1805), and Hammond (1880) reported that the early settlers repeatedly burned the woods to improve hunting prospects and pasturage for cattle. As Hammond (1880) noted for the South Carolina Piedmont: "The early settlers in this region were stock raisers and kept up the Indian practice of burning off the woods during the winter."

A more systematic survey of burning frequency was obtained by Hough (1882). Nearly all of his correspondents throughout the central hardwood region reported frequent, intentional burning, and three correspondents in Pennsylvania and Virginia volunteered estimates of the average percentage of forest land burned in a typical year. These estimates ranged from 2-14 percent of the land burned annually, equivalent to an average fire rotation period of 11 years (range of 7 to 50).

Frequent burning persisted until relatively recent times. In southern New England, Buttrick (1912) remarked that "many tracts are subject to recurring fires at frequent intervals, often annually." Graves and Fisher (1903) agreed that "woodlots which do not show some traces of fire are scarce." A major systematic survey of the southern Appalachian region was conducted by Ayres and Ashe (1905), who reported fire scars on 80 percent of the 6.5 million acres examined. Even as late as the 1920's, Logan (1975) described annual burning of woods by farmers in southwestern Wisconsin.

The advent of fire suppression programs such as the "Dixie Crusaders" and the Smokey Bear program in the 1930's and 1940's coincides well with the beginning of widespread oak regeneration problems. Based on fire scar evidence in the Great Smoky Mountains, Harmon (1982) showed a change in the fire rotation period of 10 years or less in the period prior to 1940 to over 2,000 years for the period 1940-1979. Current fire rotation periods for national forests in the central hardwood region range from 900-6,000 years (Haines and others 1975).

Fires, along with widespread grazing, led to open, park-like stands with little undergrowth (Greely and Ashe 1907, Korstian 1927). Schnur's (1937) data show that average 80-90 year old even-aged stands on site index 70 lands in the 1920's had only 6-8 trees per acre in the 2- to 4-in. diameter classes of all shade-tolerant species combined. The data of Gevorkiantz and Scholz (1948) in southwestern Wisconsin show similar trends, with an average of only 18-26 suppressed trees per acre in the 1- to 4-in. d.b.h. classes. McGill (1991) resampled fully-stocked, even-aged oak stands in the same geographical region and documented a dramatic increase in the density of shade-tolerant understory trees. Whereas stands in the earlier survey had bell-shaped size distributions, the current stands have an irregular, steeply descending distribution with the largest number of trees in the smallest size classes.

The Presettlement and Archaic Periods

While disturbances caused by European settlers and subsequent generations are probably sufficient to account for the widespread occurrence of oak forests on sites where they don't ordinarily appear to be competitive, a plausible hypothesis is needed to explain how oaks were able to dominate the landscape for thousands of years before settlers arrived. It is a difficult issue because fire would probably have had to occur more than once during the lifespan of an oak stand to prevent succession to other species, particularly if the fires were of low or moderate intensity. Yet, the available evidence suggests that Indian populations were relatively small and lightning fires relatively uncommon (Schroeder and Buck 1970, Barden and Woods 1973).

The hypothesis that fire was a major factor in accounting for the dominance of oak forests on mesic sites does not presuppose that the entire landscape had to be burned at frequent intervals. First, as already noted, many dry sites and some average sites appear to be able to maintain stable oak forests in the absence of fire. Second, sizable areas of the central hardwood region are known to have been covered by non-oak forest in presettlement times. Beech-maple forest, mixed with hemlock in some areas, covered large areas of New York, northern and central Pennsylvania, and northern Ohio. Mixed-mesophytic forest also occupied many of the good sites in West Virginia, eastern Kentucky, and central Tennessee (Sargent 1884, Braun 1950, Kuchler 1964, Whitney 1990). In the oak savanna regions of the Midwest, the role of fire is already established beyond reasonable doubt. Thus, the areas in which the frequency and impact of fire are most in question are the eastern Piedmont, the Ridge and Valley province, and the Southern Appalachian Mountains. The following is a brief overview of the available evidence in those areas and a discussion of problems that remain.

There are indeed many references by early travelers and colonists to the widespread practice of woods burning by Indians. In fact, few writers of the time who included any significant account of the vegetation failed to mention the practice or its effects on the forest. A number of these accounts, but by no means all, were reviewed by Maxwell (1910), Day (1953), and Lorimer (1985). The following description of coastal Massachusetts by Wood (1634) has many of the elements that occur frequently in these accounts:

> *There is no underwood saving in swamps and low grounds that are wet . . . for it being the custome of the Indians to burne the wood in November, when the grass is withered, and the leaves dried, it consumes all the underwood, and rubbish, which otherwise would over grow the Countrey, making it unpassable, and spoyle their much affected hunting; so that by this meanes in those places where the Indians inhabit, there is scarce a bush or bramble, or any cumbersome underwood to bee seene in the more champion ground. . .*

Morton (1632) implied that the practice was so widespread in coastal Massachusetts that trees not scorched or damaged by fire were difficult to find:

> *So that hee that will looke to finde large trees, and good tymber . . . must seeke for them, (as I and others have done) in the lower grounds where the grounds are wett when the Country is fired ... for the Salvages by this Custome of theirs, have spoiled all the rest: for this Custome hath bin continued from the beginninge. . ..*

Since the fires were often set or accidentally started during periods of dry weather, and usually no attempt was made to control them, they could spread over large areas. Loskiel (1794) noted that "these fires run on for many miles," and Morton (1632) described the typical fire as "burning continually night and day, until a shower of rain falls to quench it." In New York, Van der Donck (1656) described the woods burning as a "yearly custom" and that some fires were quite intense, "for it frequently spreads and rages with such violence, that it is awful to behold."

Russell (1983) has challenged the idea of widespread intentional burning by Indians. She notes, with some justification, that early writers did not necessarily imply widespread burning of the landscape, but only "in those places where the

Indians inhabit" (Wood 1634) and "in all places where they come" (Morton 1632). She also feels that the writers may have been biased, and exaggerated the openness of the woods in order to attract more colonists. However, the descriptions of fire use and open woods with little undergrowth are consistent among many groups of people including priests and missionaries (Loskiel 1794, Rights 1947), surveyors (Lindestrom 1656, Byrd 1728), botanists (Bartram 1791), early historians (Norris 1890, Logan 1859), and early explorers and travelers with no specific land claims in the areas described (Smith 1616, Lawson 1709, Grant 1946). In Massachusetts, independent evidence can be found which supports the accounts of Indian burning related by Morton and Wood. Colonial records of Massachusetts indicate that in 1677 the court was "informed that great damage hath happened to several persons in the outskirt plantations by Indians kindling fires in the woods in the latter part of the yeare", and passed a law limiting the times during which Indians could set fires (Hough 1882).

A more difficult problem than writer bias is probably the fact that these early accounts do not provide a systematic view of the landscape. Early explorers often traveled along rivers, where evidence of Indian activities was more likely to be seen (e.g., Lawson 1709, Bartram 1791), or used Indian paths and trading paths connecting different villages. Also, early colonists tended to settle first in those areas that had been cleared by Indians (H. S. Russell 1980) which might not be representative of the general landscape.

The diary of Col. William Byrd is therefore of particular interest because in 1728 he was involved in surveying the boundary line between Virginia and North Carolina, and was therefore confined to a compass line. The frequent references to fire and fire effects do give the impression that fire was a major factor on the landscape in that region. Byrd made several references to extensive thickets of saplings that appeared to be of fire origin, as when he reported that they "Scuffled thro' a mighty thicket, at least three miles long. The whole was one continued tract of rich high land, the woods whereof had been burnt not long before. It was then overgrown with Saplings of Oak, Hiccory, and Locust . . . ." When the Byrd party reached the mountains, near a major Indian trail, they encountered a "great fire" which Byrd attributed to Indians. Most importantly, Byrd made general remarks about fire frequency, stating that "the woods are not there burnt every year, as they generally are amongst the Inhabitants. But the dead Leaves and Trash of many years are heapt up together, which being at length kindled by the Indians that happen to pass that way, furnishing fewel for a conflagration that carries all before it." The contrast in fire regimes between these mountain forests and areas more densely settled by Indians, which Byrd considered to be subject to widespread burning each year, provides independent confirmation of accounts elsewhere by Morton (1632), Wood (1634) and others.

The low importance of shade-tolerant species over extensive areas of the Piedmont and Ridge and Valley provinces in presettlement times provides indirect but important evidence on presettlement fire frequency. Tolerant species appear quite capable of dominating the overstories on many sites (e.g., Abrams and Downs 1990, Abrams and Nowacki 1992), so we must consider why these strong successional trends did not also take place in presettlement times. If fire was indeed the principal factor restricting the occurrence of these species (cf. Kline and Cottam 1979 and Grimm 1984 for midwestern examples), then the rarity of late-successional forests on the uplands suggests the influence of fire may have been widespread and pervasive.

Scientific Evidence on Fire Frequency. Modern scientific studies can provide independent data for comparison with historical accounts. Studies of fire scars on living trees are unfortunately very limited because by the 20th century old-growth oak forest was already very rare. Apparently the only evidence for the eastern Piedmont/Appalachian region is based on a cross-section of a single large white oak in the New Jersey Piedmont, which, however, had several fire scars between the period 1641 and 1711 (Buell and others 1954). Some indication of presettlement fire frequency in other areas is given by a study by Lutz (1930) of a hemlock-beech forest on the Allegheny Plateau. In spite of the typically low fire frequency in this forest type, and the fact that the stand was located on an east-facing slope in a remote area near the headwaters of a small stream, Lutz found evidence of at least five major fire dates for the presettlement period 1725-1795. Fire scar studies should be done soon in the remaining old-growth Appalachian oak stands before the demise of old trees that were alive in presettlement times.

A promising approach to investigating presettlement fire frequency is the analysis of charcoal fragments in sediment cores from bogs and ponds. Although few studies of charcoal have yet been done, Watts (1979) and Patterson and Backman (1988) found charcoal throughout the sediment profiles in nine different sites in western Virginia, central Pennsylvania, coastal New Jersey, New York, and Massachusetts. In a number of cases there was no indication that charcoal was less abundant in the several thousand years prior to European settlement than afterward. In a site adjacent to the Little Tennessee River, Cridlebaugh (1984) also found charcoal throughout the profile. However, in this case charcoal abundance increased by an order of magnitude after A.D. 1000, when Indian agricultural activities intensified, and showed another dramatic rise at the time of European settlement.

Indian Settlement Patterns. How widespread were Indian effects on vegetation? Archaeological and historical evidence indicates that although villages were generally located near streams and rivers, Indians themselves used a wide range of environments and the pattern of use frequently shifted. Indians in the Archaic period (ca. 8000-1000 B.C.) were migratory hunter-gatherers and made the greatest use of upland habitats. In North Carolina, Ward (1983) noted that signs of the Archaic cultures "covered the Piedmont landscape, leaving a network of tracks that is hard to miss . . . The broad alluvial valleys, the rolling upland hills, and the banks of small streams were all occupied, visited, or utilized at some point during the 6,000 to 7,000-year span of the Archaic period." After the widespread adoption of agriculture (ca. A.D. 1000), there was a dramatic shift of village sites to the floodplains of major rivers and streams (Purrington 1983, Thornton 1990). However, upland sites continued to be used, perhaps as temporary base camps for deer hunting and nut harvesting (Ward 1983). In the Smoky Mountain region, 40-50 percent of food processing sites continued to occur in upland zones, including benches, coves, and saddles between mountains (Purrington 1983).

Knowledge of Cherokee villages and population levels is probably more accurate than for some other tribes, and can perhaps give some indication of the probable impact on the landscape. The Cherokee population in the early 1600's, prior to contact with European diseases, is estimated to have been between 22,000-30,000 people distributed over approximately 52,000 square miles, with an average population density of about 16 per 25 square miles (Thornton 1991). The population was concentrated in at least 60 villages along major branches of the Hiwassee, Little Tennessee, and Tugaloo rivers. Goodwin's (1977) map of known villages (ca. 1700) shows that even villages on different rivers were usually not more than 15-20 miles apart, while villages on the same river were usually only a few miles apart. Because of this dispersion of villages across the region, it is likely that Indians could have had a major impact on the intervening upland areas. As Bishop Spangenberg commented in 1752: "The woods are full of Cherokees, and we see their signs wherever we go. They are out hunting." (Rights 1947).

It is important to keep in mind that Indians, even after the advent of agriculture, were migratory and hence would have had more impact than their numbers alone might suggest. In the early 1600's, John Smith wrote that when the Indians of coastal Virginia went hunting, "they leave their habitations, and reduce themselves into companies, as the Tartars doe, and goe to the most dessert [uninhabited] places with their families, where they spend their time in hunting and fowling up towards the mountains, by the heads of their rivers, where there is plentie of game . . . Having found the Deere, they environ them with many fires, and betwixt the fires they place themselves.". Loskiel (1794) likewise noted that Indians in the mid-Atlantic region commonly set out for long hunts lasting 3-4 weeks, and often several months. In addition, warfare and trade often prompted Indians to travel astonishingly long distances. For example, it was not uncommon for the Iroquois of central New York to travel to South Carolina to make war against the Catawbas and into Florida to fight the Creeks (Byrd 1728, Myer 1971). Long-distance travel for hunting, warfare, and trade was made possible by a complex and surprisingly dense network of trails. Maps of known Indian trails, such as those in Massachusetts (Russell 1980), Pennsylvania (Wallace 1965), and the Southeast (Myer 1971) show that relatively few stands would have been located more than 15 miles from the nearest Indian trail (figure 3). This would have rendered many stands in otherwise sparsely settled areas subject to occasional accidental or intentional fires.

A final resolution of the Indian fire question is not possible at the present time. It is probably reasonable to state, however, that the available historical and scientific evidence is consistent with the hypothesis that Indian fires were widespread and had a major impact on the landscape. More evidence on charcoal deposits in sediments and fire scars in old-growth stands may help clarify the issue of local fire frequency. Also, by integrating evidence on fire size distributions in the absence of suppression (e.g., Hough 1882) with evidence on Indian populations size and distribution, it might be possible to judge whether or not fires could have been frequent enough to account for the original distribution of oaks on sites where they don't ordinarily appear to be competitive.

CONCLUSIONS

A number of factors, including poor seed production, consumption of acorns, damage to seedlings by animals, adverse spring weather, and poor development of oak seedlings under dense canopies, are known to contribute to oak regeneration failures. Each of these factors can probably lead to local oak regeneration failures at certain times and places. The degree to which the regional oak regeneration problem is caused by interactions of all of these factors is still not well known.

Figure 3—The network of recorded Indian trails in Tennessee and surrounding areas in the early colonial period, compiled by W. E. Myer in 1923 (Myer 1971).

Relatively little evidence, for example, is available on ambient levels and resulting impacts of insect defoliation of oak seedlings or deer browsing over large areas.

The principal bottleneck to successful oak regeneration, nevertheless, does not usually seem to occur in the seedling germination stage. Most mature oak stands already have hundreds or thousands of oak seedlings per acre in the understory. A major limiting factor is that these seedlings usually have slow juvenile growth and low survival rates on good sites, even after the overstory is removed. Studies have shown that the development of a shade-tolerant understory layer is particularly detrimental to adequate development of oak advance regeneration, and historical evidence suggests that most oak stands developed in situations where fire, grazing, and other disturbances periodically removed this small-tree layer. The hypothesis that a major factor in the regional oak regeneration problem has been the widespread development of shade-tolerant saplings on mesic sites after alteration of the disturbance regime is consistent with life-history traits of several of the common upland oak species, and helps explain several observed features of the regional problem. For example, the disturbance hypothesis can account for the relatively sudden increase in oak regeneration failures after the 1930's and 1940's, the geographically widespread nature of the problem, and the fact that oak regeneration has usually not been a problem on drier sites. Although limited quantitative evidence on fire frequency in presettlement times is perhaps the weakest aspect of the hypothesis, there is considerable historical and some scientific evidence that fire frequencies were much higher in presettlement and postsettlement times than at present. Additional field studies on fire history, and controlled experiments on factors affecting oak regeneration, will help resolve some of these uncertainties.

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Oak Regeneration: The Scope of the Problem

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ABSTRACT

An evaluation of oak regeneration, based on published literature and direct input from researchers in the field, is presented for 31 oak species native to the United States. The evaluated species include 12 from the white oak group, 18 from the red oak group, and one from the intermediate oak group. There are 25 species from the eastern United States and six from the western United States. Twenty of the species are indigenous to upland sites and 11 are considered bottomland species. A general summary of key silvical characteristics is provided. An attempt has been made to assess regeneration success of each species in terms of geographic location, site quality (two levels), and regeneration type (seedling, seedling sprout, or stump sprout). A qualitative evaluation of the level of research knowledge available about the regeneration of each species is given.

OVERVIEW

Quercus is the classical Latin name of the oaks. It is thought to be of Celtic derivation meaning *fine* and *tree* (Little 1979). Oak is the largest tree genus in the United States and is the most important hardwood genus. The oaks are the major component of eastern deciduous forests and dominate stands in central and southern upland forests. In addition, they are a significant component of mixed bottomland hardwoods throughout the eastern and southern United States, and occur on valley and slope sites in the semi-arid regions of the western United States. They are not found in the Great Plains region.

The oaks are of major economic importance for wood products as well as for numerous wildlife, recreation, and aesthetic uses and values in both rural and urban forests. The wood of oak species has long been known for its strength, durability, and beauty. It is widely used in products ranging from fine furniture to rough construction material, railroad cross-ties, various types of cooperage, and mine props. Acorns are a primary source of hard mast and a mainstay in the diets of many animal and bird species. The majestic oaks are known for beauty and are highly sought after for lawn and shade trees.

The oak genus (*Quercus*) is one of the eight genera of the beech family (*Fagaceae*) found worldwide. Of the estimated 500-600 species of oak, most are found in the northern hemisphere. Some 200-250 species are found in North, Central, and

South America, and 300 or more species are scattered throughout Europe, Asia, and North Africa (Little 1979, Harlow and others 1991). There are 58 recognized native oak tree species in the United States and Canada, one naturalized tree species, and about 10 native oak shrubs. There are about 125 species native to Mexico, 45 species native to Central America, five species in Colombia, and one species in Cuba (Little 1979).

For the most part, oaks are durable and relatively long-lived when compared with associated species. Ages up to 700 years have been recorded (Hora 1981). In the United States, extremely large-sized oaks have been documented. A classic example is a white oak (*Q. alba* L.) that was cut in 1913 near Lead Mine, West Virginia. This giant was 13 ft. in diameter 16 ft. at the base, and 10 ft. in diameter 31 ft. from the base (Clarkson 1964).

Unquestionably, oaks are a highly valued and important species. They have many important uses and values, and the forested land base on which they are growing is under extreme pressure for conversion to alternative land uses, as the nation's and the world's populations continue to grow and the demands for land-based resources continue to intensify.

OAK REGENERATION —IS IT A PROBLEM?

Whenever there is an abundance of any resource or commodity, and that resource or commodity is readily available to people who want it at a price they are willing to pay, then there is no problem with that particular resource. Oak in forests is in high demand for a variety of uses and values. But, the amount of oak that regenerates following a harvest or major disturbance is often less than was present in the parent stand. Or, forestland owners often want oak in their stands even when they did not have it in the previous stand. The mere fact that you want oak, and you do not get it, constitutes a problem regardless of the reasons for not getting it.

Two basic types of problems apply to failures in obtaining the desired level of oak regeneration. A scenario for the first type of problem is that a forest landowner or forest manager wants oak regeneration; however, an analysis of known biological and site information indicates that oak regeneration is highly unlikely. A scenario for the second type is that all of the biological and site data indicate that regeneration should occur, but it does not. Oak regeneration was an objective in both scenarios, but it did not occur; the bottom line in both cases is that it did not occur; therefore, oak regeneration is a problem. As research silviculturists, it is very important that we clearly distinguish between the two basic problem types so that viable research efforts are not misdirected.

In the first problem type, where we can clearly determine that the biotic and abiotic conditions were not conducive to oak regeneration, we need to clearly communicate this to the landowner or manager. It is quite probable that we can suggest appropriate cultural practices to alter the biotic or abiotic conditions so that the probability of obtaining oak regeneration is enhanced.

In contrast, the second problem scenario is more perplexing and problematic to silviculturists because, although the biological and site conditions indicate that successful oak regeneration should occur, it does not, indicating that factors may be coming into play that we do not understand. Only through a careful analysis and thorough evaluation of this second problem type will silviculturists be able to identify and prioritize oak regeneration research problems and subsequently devise research programs that will lead to new knowledge.

If we do not effectively convey the information we already have about oak regeneration, it is not an *oak regeneration problem*, it is a *management (people) problem;* yet it is still a problem. A discussion of oak technology transfer, however, is beyond the scope of this paper, but is being actively addressed by the sponsors and planners of this Oak Regeneration Symposium. In the remainder of this paper, I will briefly review some of the literature that deals with oak regeneration, summarize silvical characteristics of various oak species that are important in the regeneration process, and then evaluate the regeneration problem and the general level of knowledge about 31 oak species native to the United States.

SOME RESULTS OF OAK REGENERATION RESEARCH

A number of authors have identified oak regeneration as a problem in attempts to establish a new stand following harvesting. McLintock (1987) emphasized that obtaining adequate representation of preferred species, especially the oaks, is a high priority research area. Merritt (1979) provided a thorough and thoughtful review of problems associated with oak regeneration in eastern upland forests. Later in the same proceedings, McGee (1979) eluded to the sparse regeneration of northern red oak (*Q. rubra* L.) on higher quality sites in the Southern Appalachians. Others have identified oak regeneration as a management problem in that prescribed practices are not producing the consistent oak regeneration results desired (Beck 1970, Beck and Hooper 1986, Loftis 1983, McGee and Hooper 1970). Without release from faster growing yellow-poplar, the fate of planted or natural seedlings of southern oak species in the small openings of a group selection reproduction harvest was not encouraging after 22 years (Johnson and Krinard 1983). In the semi-arid regions of California, a statewide oak regeneration survey concluded that regeneration often was inadequate to maintain existing stands and that regeneration was highly site-specific. Blue oak (*Q. douglasii* Hook. Arn.) and valley oak (*Q. lobata* Née) regeneration tended to be poor (Muick and Bartolome 1987). In another study, Muick (1991) observed that coast live oak (*Q. agrifolia* Née), interior live oak (*Q. wislizeni* A. DC.) and canyon live oak (*Q. chrysolepis* Liebm.) were regenerating more successfully. Certainly, not all reports of oak regeneration indicate failures; there are successes. Johnson and Krinard (1988) reported that 29 years after harvest, cherrybark oak (*Q. falcata* var. *pagodifolia* Ell.) was a significant component in a southern bottomland hardwood stand. Earlier evaluations of the stand development had been less optimistic as far as the oak component was concerned.

Clark and Watt (1971) identified two basic principles that must be understood when discussing natural regeneration of upland oaks and that probably also apply to bottomland oaks and to some degree to the Western United States oaks as well:

1. The new stand will contain oak in proportion to the advance oak reproduction on the area before the harvest cut.
2. Advance oak reproduction must have a well-established root system to compete successfully with other woody vegetation (and with grasses in many Western United States oak sites).

The need to understand these two very basic principles has not changed in the past two decades. This points to a need to understand as much as we can about how oak regeneration occurs and how it gets to the stage of advance reproduction with the associated well-established root system. In other words, what are the important silvical characteristics of oak species that are important in reproduction establishment and subsequent growth and development?

OAK REGENERATION: IMPLICATIONS OF SILVICAL CHARACTERISTICS

A review of some of the more important regeneration-related silvical characteristics of oak species provides insights into possible reasons for low regeneration success or for complete failures (table 1). For the most part, eastern upland and bottomland oaks occur in association with a wide array of overstory and understory woody species. Seldom will oak occur in pure stands. On the more arid sites in the West, oak will often occur in clumps or small, pure stands; however, competition from grasses and shrubs is often severe and greatly influences regeneration establishment and early growth.

The preponderance of oak reproduction results from natural regeneration following a harvest or natural disturbance. Planting, although very limited in application, has enjoyed a wide range of success ranging from complete failures to fully stocked plantations. However, the artificial regeneration process usually requires intense culture, including competition control for one or more growing seasons and is only accomplished at a relatively high cost. Natural regeneration usually is composed of three different reproductive forms: seedlings, seedling sprouts (normally considered as advance regeneration), and stump sprouts. Of the three reproductive forms, seedlings are the slowest growing and least competitive, and stump sprouts are generally the fastest growing and most competitive. Seedling sprouts are unique because their root systems are usually well-developed compared to a seedling root; however, the top often resembles that of seedlings.

Of the 31 species reviewed in this paper, three are considered tolerant to shade, 11 are intermediate in tolerance to shade, and 17 are intolerant or very intolerant (table 1). None of the bottomland oaks tolerate flooding to any significant degree, especially flooding that occurs during the growing season (table 1). In discussions with colleagues active in bottomland oak regeneration research, there is a strong consensus that flooding is particularly detrimental to newly established seedlings. In contrast to shade and flood tolerance, however, the oaks that inhabit exposed, droughty sites appear to be quite tolerant of low moisture conditions (table 1). In general, regeneration success is relatively good on poorer sites where competition from associated species is often less intense.

Juvenile growth of oak species is generally slower than or equal to associated competition. Sixteen of the species reviewed grew slower than competitors, eight grew about as fast, and only five had juvenile growth rates that were faster than associated competitors (table 1). Acorn production of oak species is sporadic and unpredictable at best. In general, bumper acorn crops are required to obtain significant seedling establishment. Predation by wildlife and insects coupled with acorn mortality from disease and adverse weather conditions during the intervening years between bumper crops are believed to restrict greatly the acorns that are available to germinate and develop as regeneration. The analysis of available oak regeneration research information suggests that high levels of acorn production generally occur at intervals ranging from 3 to 7 years or more (table 1).

Table 1—Summary of regeneration-related silvical characteristics[1] of 31 oak species native to the United States, noting important uses, values, and relative assessment of the available research knowledge

Scientific Name (common name)	---- Tolerance ----			Acorn Production -- (years) --		Juvenile Growth Rate[4]	Uses and Values[5]	Research Knowledge[6]
	Shade[2]	Flood[3]	Drought[3]	Normal	High			
Subgenus: Leucobalanus: White Oaks								
Q. agrifolia Née (coast live oak)	Tol[7]	N/A	Inte	Unk	Unk	slower	W,O,F,S	Lim
Q. alba L. (white oak)	Inte	N/A	Intol	2-4	4-10	slower	W,O,F, T,S	Ext
Q. bicolor Willd. (swamp white oak)	Inte	Tol	N/A	2-4	3-5	slower	W,O,F,T	Mod
Q. garryana Dougl. ex Hook. (Oregon white oak)	Inte	Tol	Tol	Unk	3-5	slower	W,O,F, T,S	Mod
Q. lyrata Walt. (overcup oak)	Inte	Tol	N/A	1-2	3-4	competitive	W,F,T	Lim
Q. macrocarpa Michx. (bur oak)	Inte	N/A	Tol	2-4	2-3	faster	W,F,T,S	Lim
Q. michauxii Nutt. (swamp chestnut oak)	Intol[8] Inte	Inte	N/A	2-4	3-5	competitive	W,F,T	Mod
Q. prinus L. (chestnut oak)	Inte	N/A	Tol	erratic	4-5	slower	W,F,T,S	Mod
Q. stellata Wangenh. (post oak)	Intol	N/A	Tol	2-4	2-3	slower	W,O,F, T,S	Lim
Q. virginiana Mill. (live oak)	Inte	Inte	Inte	Unk	Unk	Unk	W,O,F,S	Lim
Q. muehlenbergii Engelm. (chinkapin oak)	Intol	N/A	Tol	Unk	Infreq.	slower	W,F,S	Lim
Q. lobata Née (valley oak)	Intol[9]	Intol	N/A	Unk	2-3	slower	W,O,F	Lim
Subgenus: Erythrobalanus: Red and Black Oaks								
Q. coccinea Muenchh. (scarlet oak)	V. Intol	N/A	Inte-Tol	erratic	3-5	faster	W,O,F, T,S	Mod
Q. douglasii Hook & Arn. (blue oak)	Intol	N/A	Tol	2-3	5-8	slower	W,F,S	Lim
Q. ellipsoidalis E. J. Hill (northern pin oak)	Intol[10]	N/A	Tol	2-4	3-5	competitive	W,O,F,S	Lim
Q. falcata Michx. (southern red oak)	Inte	N/A	Tol	Unk	Unk	competitive	W,O,F, T,S	Mod
Q. pagoda Raf. (cherrybark oak)	Intol	Inte	N/A	1-2	2-4	faster	W,O,F, T,S	Mod-Ext
Q. ilicifolia Wangenh. (bear oak)	V. Intol[10]	N/A	Tol	Unk	Unk	slower	W,F,S,	Lim

Table 1—Summary of regeneration-related silvical characteristics[1] of 31 oak species native to the United States, noting important uses, values, and relative assessment of the available research knowledge (Continued)

Scientific Name (common name)	---- Tolerance ----			Acorn Production -- (years) --		Juvenile Growth Rate[4]	Uses and Values[5]	Research Knowledge[6]
	Shade[2]	Flood[3]	Drought[3]	Normal	High			
Q. imbricaria Michx. (shingle oak)	Intol	Inte-Tol	Intol	Unk	Unk	competitive	W,O,F,T,S	Lim
Q. kelloggii Newb. (California black oak)	Intol	Intol	Intol	2-4	3-5	slower	W,O,F,T,S	Lim
Q. laevis Walt. (turkey oak)	Intol	N/A	Tol	1-2	2-3	competitive	W,F,S	Lim
Q. laurifolia Michx. (swamp laurel oak, diamondleaf)	Inte-Tol	Tol	N/A	Unk	Unk	Unk	W,O,F,	Lim
Q. marilandica Muenchh. (blackjack oak)	Intol[10]	N/A	Tol	Unk	Unk	slower	W,F,S,T	Lim
Q. nigra L. (water oak)	Intol	Inte	N/A	1-2	1-2	slower	W,O,F,T,S	Lim
Q. nuttallii Palmer (Nuttal oak)	Intol Inte	Inte-Tol	N/A	2-4	3-4	faster	W,O,F,T	Lim
Q. palustris Muenchh. (pin oak)	Intol	Inte-Tol	N/A	2-4	4-6	faster	W,O,F,T	Lim
Q. phellos L. (willow oak)	Intol	Intol-Inte	Intol	1-2	1-2	competitive	W,O,F,T	Lim
Q. rubra L. (northern red oak)	Inte	N/A	Intol	2-4	2-5	slower	W,O,F,T,S	Ext
Q. shumardii Buckl. (Shumard oak)	Intol	Intol	Intol	2-4	Unk	competitive	W,O,F,T	Lim
Q. velutina Lam. (black oak)	Inte	N/A	Inte	2-4	2-3	slower	W,F,T,S	Mod
Subgenus: Protobalanus: Intermediate Oaks								
Q. chrysolepis Liebm. (canyon live oak)	Tol	N/A	Inte	2-4	2-4	slower	W,O,F,T,S	Lim

[1] Unless otherwise indicated, the information is derived from Burns and Honkala 1990; Little 1979; Harlow and others 1991; Elias 1980.
[2] Five levels of shade tolerance: V. Tol = very tolerant; Tol = tolerant; Inte = intermediate; Intol = intolerant; V. Intol = very intolerant.
[3] Three levels of tolerance: Tol = tolerant; Inte = intermediate; Intol = intolerant; N/A = not applicable.
[4] Growth rate relative to associated species: slower, competitive, faster.
[5] Uses and values are W = wildlife; O = ornamental; F = fuel; T = timber/fiber; S = site protection/watershed.
[6] Ext = extensive; Mod = moderate; Lim = limited.
[7] Muick 1991.
[8] Johnson and Krinard 1983.
[9] Standiford 1991.
[10] Author's field observations.

SUMMARY AND CONCLUSIONS

Oak is the largest tree genus in the United States and is the most important hardwood. The oaks enjoy a full array of values and uses, and the demand for these values and uses will only increase in the future. In terms of the level of knowledge available about oak regeneration, we are at a distinct disadvantage. We have a significant pool of knowledge for only three of the 31 species reviewed. We have a modest amount of regeneration information for seven species and only limited information on the remaining 21 species (table 1). For the 27 native oak species that were not reviewed, there is virtually no information available.

The regeneration-related silvical characteristics of the 31 oak species, as a group, indicate that the oaks:

1. Are intolerant or intermediate in tolerance to shade
2. Are intolerant of flooding or inundation
3. Tend to be drought tolerant
4. Grow at rates slower than or equal to associated competitors
5. Produce acorns at sporadic and unpredictable intervals with bumper crops being produced at 3- to 7-year intervals.

Based on the above summary, there is little question that successful natural oak regeneration is difficult to achieve consistently without silvicultural intervention. Even with silvicultural intervention, the regeneration results will be quite variable because of unpredictable and uncontrollable environmental conditions and a limited amount of knowledge about the processes and interactions associated with oak regeneration (table 2).

Oak regeneration is a problem and the problem is widespread. Many of the problems can be solved by utilizing information that is already available, but there is a cost involved, which will have to be addressed by forest managers and forest landowners. Other problems with oak regeneration will require a major research commitment.

What we learn at this Oak Regeneration Symposium will clarify our vision of the most important problem areas and allow us to initiate research programs to provide much-needed answers.

Table 2a.—Evaluation of regeneration for Eastern United States upland white oak species/species groups as a function of site quality and regeneration origin.

Species/ Species Group	Site Quality[1]	Regeneration Origin (Probability of Occurrence)[2]		Overall Regeneration Problem[3]
White Oak	High	Seedling	(Med)	SEVERE
		Seedling sprout	(Med)	SEVERE
		Stump sprout	(Low)	SEVERE
	Low	Seedling	(High)	SEVERE
		Seedling sprout	(High)	MODERATE
		Stump sprout	(High)	MINIMAL
Chestnut Oak	High	Seedling	(Med)	SEVERE
		Seedling sprout	(Med)	MODERATE-SEV
		Stump sprout	(Med)	MODERATE
	Low	Seedling	(High)	MODERATE-SEV
		Seedling sprout	(High)	MODERATE
		Stump sprout	(High)	MINIMAL
Bur Oak Post Oak Chinkapin Oak	High	Seedling	(N/A)	N/A
		Seedling sprout	(N/A)	N/A
		Stump sprout	(N/A)	N/A
	Low	Seedling	(Med)	MODERATE-SEV
		Seedling sprout	(High)	MODERATE-MIN
		Stump sprout	(High)	MINIMAL

[1] High = site index$_{50}$ 75 and greater; Low = site index$_{50}$ less than 75.

[2] High = high probability of regeneration of specified type occuring on specified site; Med = medium probability; Low = low probability; N/A = not applicable, species do not occur on site indicated.

[3] Qualitative evaluation by the author based on published information, discussion with colleagues, and field observation: SEV = severe, MOD = moderate, MIN = minimal, N/A = not applicable.

Table 2b.—Evaluation of regeneration for Eastern United States bottomland white oak species/species groups as a function of site quality and regeneration origin.

Species/ Species Group	Site Quality[1]	Regeneration Origin (Probability of Occurrence)[2]		Overall Regeneration Problem[3]
Swamp Oak Swamp Chestnut Oak	High	Seedling	(Med)	SEVERE
		Seedling sprout	(Med)	MODERATE-SEV
		Stump sprout	(Low)	MODERATE
	Low	Seedling	(N/A)	N/A
		Seedling sprout	(N/A)	N/A
		Stump sprout	(N/A)	N/A
Overcup Oak	High	Seedling	(N/A)	N/A
		Seedling sprout	(N/A)	N/A
		Stump sprout	(N/A)	N/A
	Low	Seedling	(Med)	MODERATE
		Seedling sprout	(Med)	MODERATE
		Stump sprout	(Med)	MODERATE
Live Oak	High	Seedling	(Med)	N/A
		Seedling sprout	(Low)	N/A
		Stump sprout	(High)	N/A
	Low	Seedling	(Med)	MODERATE
		Seedling sprout	(Med)	MODERATE-MIN
		Stump sprout	(High)	MINIMAL
		Root sprouts	(High)	MINIMAL

[1] High = site index$_{50}$ 75 and greater; Low = site index$_{50}$ less than 75.

[2] High = high probability of regeneration of specified type occuring on specified site; Med = medium probability; Low = low probability; N/A = not applicable, species do not occur on site indicated.

[3] Qualitative evaluation by the author based on published information, discussion with colleagues, and field observation: SEV = severe, MOD = moderate, MIN = minimal, N/A = not applicable.

Table 2c.—Evaluation of regeneration for Eastern United States upland red oak species/species groups as a function of site quality and regeneration origin.

Species/ Species Group	Site Quality[1]	Regeneration Origin (Probability of Occurrence)[2]		Overall Regeneration Problem[3]
Northern Red Oak Black Oak	High	Seedling	(Med)	SEVERE
		Seedling sprout	(Med)	SEVERE-MOD
		Stump sprout	(Low)	MODERATE-SEV
	Low	Seedling	(Med)	SEVERE
		Seedling sprout	(Med)	MODERATE
		Stump sprout	(High)	MINIMAL
Scarlet Oak Southern Red Oak Northern Pin Oak	High	Seedling	(Low)	SEVERE
		Seedling sprout	(Med)	SEVERE-MOD
		Stump sprout	(Low)	MODERATE-SEV
	Low	Seedling	(Med)	SEVERE
		Seedling sprout	(Med)	MODERATE-MIN
		Stump sprout	(High)	MINIMAL
Turkey Oak Shingle Oak Blackjack Oak	High	Seedling	(N/A)	N/A
		Seedling sprout	(N/A)	N/A
		Stump sprout	(N/A)	N/A
	Low	Seedling	(Med)	SEVERE
		Seedling sprout	(Med)	MODERATE
		Stump sprout	(High)	MINIMAL
Bear Oak	High	Seedling	(N/A)	N/A
		Seedling sprout	(N/A)	N/A
		Stump sprout	(N/A)	N/A
	Low	Seedling	(High)	MODERATE-SEV
		Seedling sprout	(Low)	MODERATE
		Stump sprout	(High)	MODERATE

[1] High = site index$_{50}$ 75 and greater; Low = site index$_{50}$ less than 75.

[2] High = high probability of regeneration of specified type occuring on specified site; Med = medium probability; Low = low probability; N/A = not applicable, species do not occur on site indicated.

[3] Qualitative evaluation by the author based on published information, discussion with colleagues, and field observation: SEV = severe, MOD = moderate, MIN = minimal, N/A = not applicable.

Table 2d.—Evaluation of regeneration for Eastern United States bottomland red oak species/species groups as a function of site quality and regeneration origin.

Species/ Species Group	Site Quality[1]	Regeneration Origin (Probability of Occurrence)[2]		Overall Regeneration Problem[3]
Cherrybark Oak Shumard Oak	High	Seedling	(Med)	SEVERE-MOD
		Seedling sprout	(Med)	MODERATE
		Stump sprout	(Low)	SEVERE
	Low	Seedling	(N/A)	N/A
		Seedling sprout	(N/A)	N/A
		Stump sprout	(N/A)	N/A
Water Oak Willow Oak Nuttall Oak	High	Seedling	(Med)	SEVERE
		Seedling sprout	(Med)	SEVERE-MOD
		Stump sprout	(Med)	MODERATE-SEV
	Low	Seedling	(Med)	SEVERE
		Seedling sprout	(Med)	MODERATE
		Stump sprout	(High)	MINIMAL
Swamp Laurel Oak or Diamondleaf Pin Oak	High	Seedling	(N/A)	N/A
		Seedling sprout	(N/A)	N/A
		Stump sprout	(N/A)	N/A
	Low	Seedling	(Med)	MODERATE
		Seedling sprout	(Med)	MODERATE-MIN
		Stump sprout	(High)	MINIMAL

[1] High = site index$_{50}$ 75 and greater; Low = site index$_{50}$ less than 75.

[2] High = high probability of regeneration of specified type occuring on specified site; Med = medium probability; Low = low probability; N/A = not applicable, species do not occur on site indicated.

[3] Qualitative evaluation by the author based on published information, discussion with colleagues, and field observation: SEV = severe, MOD = moderate, MIN = minimal, N/A = not applicable.

Table 2e.—Evaluation of regeneration for Western United States oak species/species groups (subgenuses combined) as a function of site quality and regeneration origin.

Species/ Species Group	Site Quality[1]	Regeneration Origin (Probability of Occurrence)[2]		Overall Regeneration Problem[3]
Coast Live Oak Oregon White Oak	High	Seedling	(N/A)	N/A
		Seedling sprout	(N/A)	N/A
		Stump sprout	(N/A)	N/A
	Low	Seedling	(Med)	MODERATE-SEV
		Seedling sprout	(Unknown)	UNKNOWN
		Stump sprout	(High)	MINIMAL
Valley Oak Blue Oak	High	Seedling	(N/A)	N/A
		Seedling sprout	(N/A)	N/A
		Stump sprout	(N/A)	N/A
	Low	Seedling	(Med)	SEVERE
		Seedling sprout	(Unknown)	UNKNOWN
		Stump sprout	(Med)	MODERATE
California Black Oak	High	Seedling	(N/A)	N/A
		Seedling sprout	(N/A)	N/A
		Stump sprout	(N/A)	N/A
	Low	Seedling	(Low)	SEVERE
		Seedling sprout	(Unknown)	UNKNOWN
		Stump sprout	(High)	MINIMAL
Canyon Live Oak	High	Seedling	(N/A)	N/A
		Seedling sprout	(N/A)	N/A
		Stump sprout	(N/A)	N/A
	Low	Seedling	(High)	MODERATE
		Seedling sprout	(Unknown)	UNKNOWN
		Stump sprout	(High)	MINIMAL

[1] High = site index$_{50}$ 75 and greater; Low = site index$_{50}$ less than 75.

[2] High = high probability of regeneration of specified type occuring on specified site; Med = medium probability; Low = low probability; N/A = not applicable, species do not occur on site indicated.

[3] Qualitative evaluation by the author based on published information, discussion with colleagues, and field observation: SEV = severe, MOD = moderate, MIN = minimal, N/A = not applicable.

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The Biology of Oak Regeneration

Ecology and Physiology of Oak Regeneration

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ABSTRACT

Obtaining adequate oak regeneration in hardwood stands is a problem complicated by the lack of a lucid understanding of species biology. Under heavy shade, relatively little morphological acclimation, low photosynthetic capacity, and high respiration contribute to an overall low capacity to compete with tolerant species. When released, oaks usually do not respond as quickly as their intolerant competitors, because of relatively lower compatibility with an open environment. Yet, conservative growth characteristics like early root growth and deep root systems, as well as physiological characteristics such as high water use efficiency and stomatal closure only at very low water potentials, enable oaks to compete more successfully on drier sites. Silvicultural practices aimed at establishing oak regeneration must enhance environmental conditions complimentary to oak biology.

INTRODUCTION

Other papers in this symposium address the many problems associated with oak regeneration and the silvicultural and management techniques that have been or could be used to alleviate those problems. It is obvious that much progress has been made, but there are unanswered questions and problems to be solved. Two of the major unresolved problems are: (1) Absence of adequate advance regeneration and knowledge of methods for obtaining it, and (2) Slow juvenile growth rate of oaks and their slow response to release (Hodges 1987, Crow 1988). Resolution of such problems requires an understanding of the biology of the species.

This paper will examine the current state of knowledge regarding the ecology and physiology of oak seedlings and relate that information to oak regeneration. A recent paper by Kolb and others (1990) presented results for northern red oak (*Quercus rubra* L.) and an excellent review of oak growth response to resource limitation. They discussed the growth strategy of red oak in relation to ecological requirements for regeneration. We will review much of that material, but the emphasis will be on physiological and morphological adaptations as they relate to regeneration. A basic assumption we have made is that regeneration and subsequent composition of a forest community is determined by: (1) microclimate and edaphic factors, (2) morphological and physiological characteristics of the species present, and (3) interaction between the two.

The relationship between site quality and oak regeneration has been extensively reviewed by other papers in this symposium. In general, obtaining oak regeneration is not a problem, or far less of a problem, on drier or below-average sites than on good sites (Arend and Gysel 1952, Loftis 1988, Hodges unpublished). Therefore, we will primarily discuss oak regeneration on the better upland and bottomland sites. We will consider ecological and physiological adaptations and how they act to make the species or plant more compatible with its environment and thus influence oak regeneration. There are differences between oak species, but most research has been on species of greater occurrence and commercial importance such as northern red oak, white oak (*Q. alba* L.), and cherrybark oak (*Q. pagoda* Raf.). That research will be emphasized, but exceptions will be noted.

NATURAL REGENERATION

Oaks can be regenerated by natural and artificial means. Some problems encountered are common to both regeneration methods while others are not. We will consider the two methods separately by examining ecological and physiological factors as they relate to the regeneration process and the problems involved.

Germination

Acorn production is highly erratic from year to year, and losses due to insects, birds, and mammals can be very high (see other papers in this symposium for references and detailed information on acorn production, acorn losses, storage, and acorn germination). Once acorns are on the ground, deterioration can be quite rapid, usually due to desiccation but also to excessive heat or cold. Also, on bottomland sites flood waters can wash a site virtually clean of acorns. In any event, it is extremely rare for acorns to survive past the first growing season after dispersal.

Despite these losses, mast production over time generally provides sufficient acorns so that germination *per se* is seldom a limiting factor for seedling establishment on most sites (see paper by Lorimer, this symposium). Burial by rodents and birds and coverage by sediment and debris help assure favorable conditions for acorn germination (Darley-Hill and Johnson 1981, Crow 1988, Deen and Hodges 1990). On upland and bottomland sites containing mature oaks, it is not uncommon to find 12,000 or more new germinants per hectare beneath an existing stand, even in deep shade (Hodges unpublished, Carvell and Tryon 1961, Beck and Hooper 1986, Merritt and Pope 1991). However, on mesic upland and floodplain sites, few of these seedlings will survive to the second growing season.

Survival and First-year Growth

Factors influencing early survival and growth of seedlings beneath a stand may be very different from those determining growth of older seedlings. Initial survival and early growth of oak seedlings beneath a dense canopy are primarily dependent on stored food reserves in the acorns and not on current photosynthate production (Wassink and Richardson 1951, Grime and Jeffrey 1965, Musselman and Gatherum 1969, Crow 1988). Under low light, first-year oak seedlings usually produce only one growth flush (Phares 1971, Crow 1988), which is determined by stored food in the acorns (Richardson 1956). Once cotyledon reserves are depleted, seedlings must survive on photosynthate produced by new leaves. Light then becomes a limiting factor for survival and growth (Tubbs 1977, Hanson 1986, Crow 1988). In fact, the inability to maintain a positive carbon balance in low light beneath mature stands may be the most likely reason for lack of oak advance regeneration in those stands (Musselman and Gatherum 1969). At low light intensities, CO_2 uptake and photosynthate production may be restricted by a lack of energy for photochemical reactions, and by stomatal resistance to CO_2 diffusion. Wuenscher and Kozlowski (1970) found that net photosynthesis of some oak species was not saturated until light intensity was high enough to cause complete stomatal opening.

Light intensity near the floor of hardwood stands is often at or below the compensation point for oaks. This low light intensity is often due not so much to a dense main canopy as to a nearly continuous mid-canopy or multi-storied layer of tolerant vegetation below the main canopy (Janzen and Hodges 1985, Hodges 1987, Janzen and Hodges 1987, Pubanz and Lorimer 1992). For northern red oak in the first growth flush, Hanson (1986) found that the level of photosynthetically active radiation needed for a positive carbon balance was about 30 μmol m^2 s^{-1}. Light levels in dense northern hardwood stands (Hanson 1986, Crow 1988, Pubanz and Lorimer 1992) and southern bottomland hardwood stands (Lockhart 1992, Hodges unpublished) are often below that level, so carbohydrate reserves used in respiration exceed that produced by photosynthesis, and the new seedlings eventually die.

Although light is a dominant environmental factor limiting seedling establishment under dense canopies, soil moisture may also limit establishment. Root growth of oaks, especially white oaks, begins, and may be quite extensive, before the shoot emerges. Root regeneration and root growth are very sensitive to soil moisture stress (Larson and Whitmore 1970, Larson 1980). In northern red oak, root initiation and growth ceased at soil osmotic potentials between -0.4 and -0.6 MPa (Larson and Whitmore 1970). Even on floodplain sites, greater seedling densities and survival may occur on the wetter micro-sites (Jones and Sharitz 1990). However, cherrybark oak seems less sensitive to root competition than many of its competitors (Jones and others 1989).

Juvenile Growth Phase

Numerous studies have shown that successful natural regeneration of eastern oaks requires the presence of advance regeneration of a number and size which can compete successfully with other species (Beck 1970, Sander 1972, Johnson 1975, Loftis 1983). Large numbers of oak seedlings are common on good sites, but they are typically small ($<$30 cm tall) and incapable of rapid height growth after release (Beck 1970, Sander 1972, Johnson 1979, Janzen and Hodges 1987). Johnson (1975) found that Nuttall oak (*Q. nuttallii* Palmer) seedlings can become established beneath a stand and survive for many years with as little as 2 hours sunlight daily, but height growth was extremely slow. Partial cuttings of various types (thinning, improvement, shelterwood, single-tree selection) may greatly increase stocking of oaks, but these practices do not assure growth to a size necessary for competing successfully with associated species (Loftis 1979, 1983; Hill and Dickmann 1988; Martin and Hix 1988).

The above findings appear anomalous in light of the many studies which have shown photosynthesis is saturated and maximum growth of oak seedlings occurs at 30-50 percent of full sunlight (Kramer and Decker 1944, Bourdeau 1954, Loach 1967, Musselman and Gatherum 1969, Phares 1971, Hodges 1987). For example, maximum biomass growth of cherrybark oak occurred at 27-53 percent of full sunlight, but height growth at 8 percent was as good as at full sunlight (table 1).

What then is the reason for the slow juvenile growth rate of oak seedlings? The answer may reside in the ecological and physiological differences between oaks and the species with which they must compete for survival and dominance of the site (Kolb and others 1990). Often the main competition is between oak seedlings and a midstory and understory of more tolerant species (Beck 1970,Sander 1972, Janzen and Hodges 1985, Beck and Hooper 1986, Hodges 1987).

Table 1—Influence of shade on growth and biomass partitioning in seedlings of cherrybark oak[1]

Sun	------- Year 1 ------				------- Year 2 ------			
(percent)	Height	Stem	Root	R/S[2]	Height	Stem	Root	R/S[2]
	(cm)	----- *(g)* ------			*(cm)*	----- *(g)* ------		
100	22.0	1.59	5.05	3.18	49.8	10.88	25.75	2.37
53	32.6	3.19	8.98	2.82	117.4	77.94	96.44	1.24
27	29.7	1.46	3.68	2.52	94.5	47.60	52.92	1.11
8	22.1	.78	1.98	2.53	58.5	9.48	14.98	1.58

[1] Seedlings were grown in shade houses covered with saran shade cloth. Soil moisture was maintained at or near field capacity in all plots. These unpublished data are averages for two studies replicated in time at the same location.

[2] Root/shoot ratio.

Shade tolerance is the ability of a species to persist in a low light environment. Kramer and Kozlowski (1979) defined shade tolerant species as those which reach a maximum rate of net photosynthesis at relatively low light intensities. Oak species exhibit a range in tolerance from moderately tolerant to intolerant, with white oaks generally more tolerant than red oaks (McQuilkin 1975, McGee 1981). Woody species with which oaks may compete during their life cycle vary in tolerance from very tolerant, for those occurring beneath a mature stand, to intolerant, for those growing only under more open conditions.

Mechanisms of shade tolerance are related to morphological and physiological adaptations. Some authors have suggested that there is a shade-tolerant growth form (morphology) which permits long-term survival of seedlings (Kohyama 1980, Hara 1987). Coupled with this species-specific growth form may be differences in phenology, photosynthesis, respiration, water use efficiency, and growth rates which permit the species to survive and grow under shade conditions (Grime and Jeffrey 1965, Loach 1970, Matsuda and McBride 1986, Matsuda and others 1989).

McGee (1975, 1986) reported that most tolerant species began budbreak earlier under forest canopies than in open clearcuts. This observation applied to six oak species as well. He suggested that the propensity of some species to initiate growth early under a canopy increases their shade tolerance by allowing some leaf development before crown closure.

Morphological acclimations in plants are thought to occur in response to limited resources (Schulze and others 1983, Johnson and Thornley 1987). When grown under shade, seedlings of most woody species will partition their growth to favor leaf growth and/or leaf area ratio as well as shoot/root ratio (Musselman and Gatherum 1969; Kolb and Steiner 1990a, 1990b), which should favor more effective utilization of the limited light resource. Oaks follow this pattern (figure

1, table 1), but the greater partitioning to shoot growth may not occur in the first growing season (Gottschalk 1987, Kolb and Steiner 1990a, Hodges present paper).

Although these morphological changes should improve the light-capturing ability of oaks, they do not seem to improve growth relative to tolerant understory species (Loach 1970). In fact, morphological acclimations of this type seem to be more important for intolerant species such as yellow-poplar (*Liriodendron tulipifera* L.) and American sycamore (*Platanus occidentalis* L.) than for oaks (Loach 1970, Jones and others 1989, Kolb and Steiner 1990a).

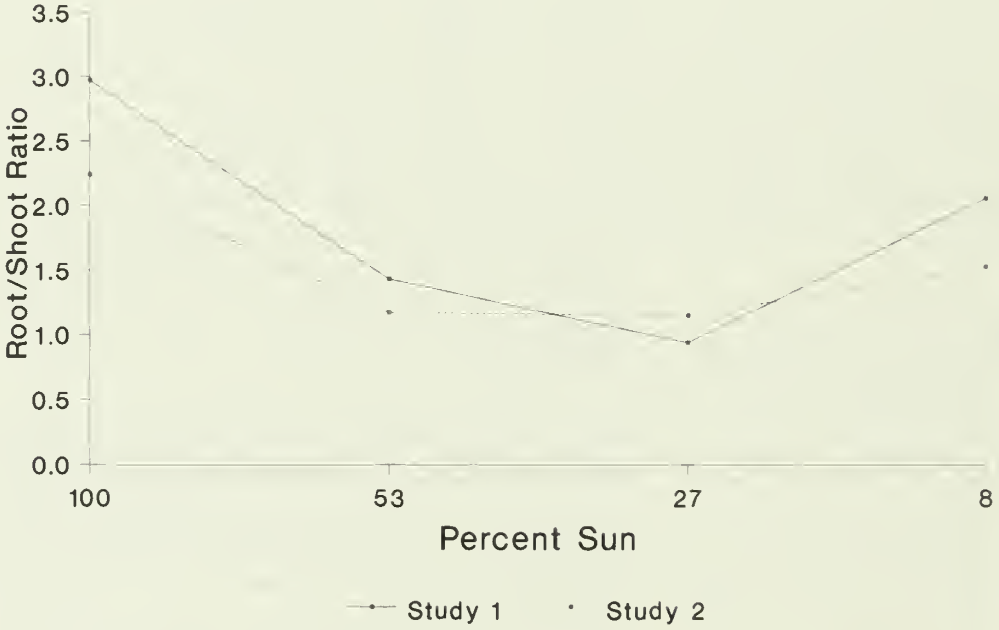

Figure 1—Influence of shade on root/shoot dry weight ratios of 2-year-old cherrybark oak seedlings grown in shade houses. Leaves are not included with shoots. Studies were replicated in time at the same location. (Unpublished data, Mississippi State University.)

Physiological acclimations to shade occur within and between species. Studies with oaks have shown acclimations in shade foliage that, when compared with sun foliage, include higher rates of net photosynthesis at low light levels, lower respiration rates, and higher levels of chlorophyll per unit of leaf area (Loach 1967). However, when compared with more tolerant species at low light intensities, oaks generally have: (1) a higher light compensation point for photosynthesis and less efficient use of "light flecks" or short bursts of light (Loach 1967, Woods and Turner 1971, Teskey and Shrestha 1985); (2) about the same or lower rates of net photosynthesis (Grime and Jeffrey 1965, Wuenscher and Kozlowski 1970, Farmer 1980); (3) as high or higher rates of respiration (Went 1957; Loach 1967; Wuenscher and Kozlowski 1970, 1971; Teskey and Shrestha 1985; Collier and others 1992); (4) slower stomatal opening and/or greater stomatal resistance to CO_2 diffusion (Woods and Turner 1971, Wuenscher and Kozlowski 1971, Davies and Kozlowski 1974, Teskey and Shrestha 1985); (5) lower quantum yield (Teskey and Shrestha 1985); (6) higher water use efficiency (Wuenscher and Kozlowski 1971, Teskey and Shrestha 1985); and (7) higher saturating light intensity for photosynthesis (Wuenscher and Kozlowski 1970, Bazzaz and Carlson 1982, Teskey and Shrestha 1985). These differences in morphological and physiological characteristics explain why oaks generally do not compete successfully in the understory on good sites.

Response of Seedlings to Release

Numerous studies have shown that large numbers of advance oak regeneration will not necessarily assure acceptable oak regeneration even if released by complete clearcutting (Beck 1970; Sander and Clark 1971; Sander 1972; Johnson 1979; Loftis 1983, 1988, 1990; Janzen and Hodges 1987). One reason is that, even though the overstory is removed, the oaks may still have to compete with a dense former understory of larger and usually more tolerant seedlings, saplings, and sprouts (Johnson and Jacobs 1981; Janzen and Hodges 1985; Beck and Hooper 1986; Hix and Lorimer 1990, 1991). These species usually have well-developed root systems and ample foliage which enable them to respond faster to release than oak seedlings.

Another, and likely more important, reason for oak regeneration failure is the slow growth rate of recently released seedlings (Beck 1970, Sander 1972, McQuilkin 1975, Janzen and Hodges 1987, Hix and Lorimer 1990). Northern red oak (Dickson 1991), cherrybark oak (Hodges and Janzen 1987) and probably most other oaks, have a conservative growth strategy in which photosynthate resources of the young seedlings are devoted first to building a root system. If, at the time of release, the seedling does not have a large root system and adequate shoot height (about 1.2 m for northern red oak) (Sander 1972), shoot growth will be slow until the root system develops.

Physiologically, oaks are not as compatible with conditions in an open environment as are many of their competitors, especially the intolerant species. Bazzaz and Carlson (1982) found physiological flexibility to be much greater in early successional species than in late successional species. Early successional species were found to be capable of responding to light so that they become more like shade plants when grown in the shade, but late successional species were unable to make the converse switch when grown in a high-light environment. Photosynthetic rates for yellow-poplar are higher than for northern red oak except at very low light intensities, yet when released the rates are much higher at high light intensities. Also, photosynthesis in oak is saturated at a much lower light intensity (Loach 1967).

Work by McGee (1975, 1986, 1988) suggests yet another possible reason for the slow growth of oak seedlings following release. He observed that budbreak in several oak species when grown under shade was earlier than when grown in the open. Thus, early budbreak of the released seedlings will increase the likelihood of freeze damage and retarded development.

Coppice Regeneration

Sprouts are an extremely important source of regeneration for most oaks, especially on xeric sites. Paul Johnson (this symposium) gives an extensive discussion of sprouts, their origin, and growth rates. Sprouts can originate in several ways, but the form that is most important for eastern oak regeneration is stump sprouts, that include seedling sprouts. These sprouts originate from dormant buds at or near the root collar. As long as the crown of the tree or seedling is attached, these buds are suppressed by growth regulators produced in the crown. When the tree or seedling is severed, the resulting sprouts show very rapid height growth. They may produce four or more flushes per year and more than 1 m of growth (Johnson 1979, Reich and others 1980).

Physiological reasons for the more rapid growth of stump sprouts is not fully understood, but in the case of larger stumps it certainly involves greater carbohydrate reserves and better absorption of water and nutrients because of the large root system. In the case of seedling sprouts, it apparently also involves a shift in the allocation of resources to favor shoot growth, an increase in stomatal conductance and carbon dioxide exchange rates, and/or increased hydraulic conductivity of the stem as opposed to intact seedlings.

Severing seedlings at time of release has been shown to partially alleviate the slow response of intact seedlings (figure 2) (Janzen and Hodges 1987, Kruger and Reich 1989, Lockhart 1992). Lockhart (1992) found that sprout shoots of cherrybark oak were the greatest sink for recently produced photosynthates and stored reserves. This change in allocation pattern allowed sprouts to maintain top growth over a longer period of time compared to intact seedlings. Sprout leaves of northern red oak (Kruger and Reich 1989) and cherrybark oak (Lockhart 1992) showed increased stomatal conductance over those from intact seedlings. In northern red oak there was also an increase in carbon dioxide exchange rate, but this was not observed in cherrybark oak.

Vessel size is known to influence water transport through the stem (Abrams 1990). The vascular system of seedling sprouts may be quite different from that of intact seedlings (Blake and Tschaplionski 1986) and may permit faster movement of water through the stem, thus in lower moisture deficits in seedlings.

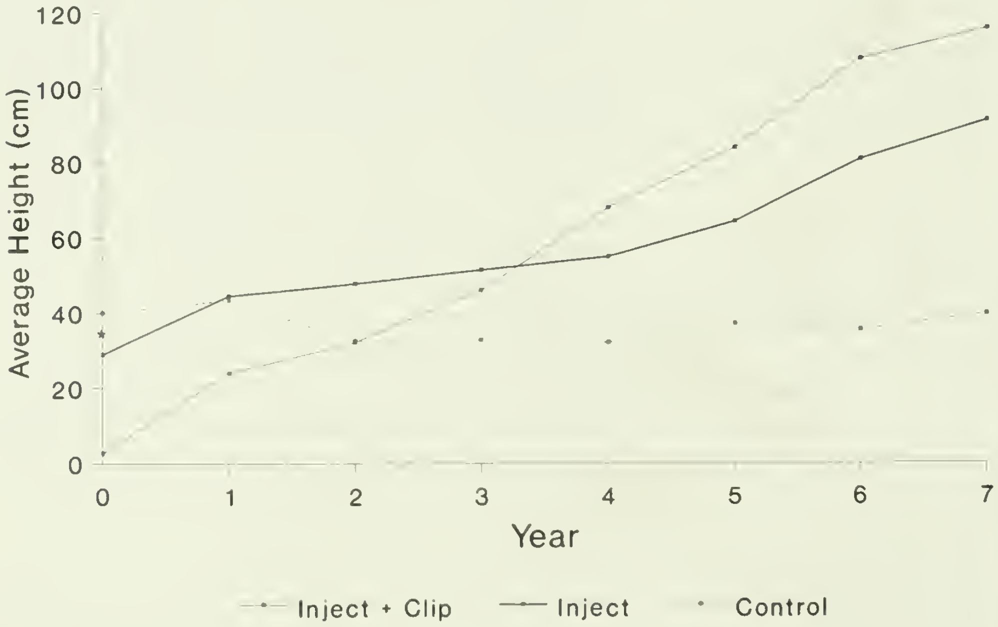

Figure 2—Height growth of bottomland oaks after removal of competing species in the midstory and understory by herbicidal injection. In the inject + clip treatment, tops of all oak seedlings were cut 2.5 cm above groundline. The asterisk indicates initial height of clipped seedlings (Janzen and Hodges 1987).

Site Quality and Disturbance

Other papers in this symposium emphasize the importance of site quality in determining the ease of obtaining oak regeneration and the role of disturbances in the origin of current oak stands. The relative ease with which certain species of oaks can be regenerated on xeric and lower quality sites appears to be a function of differences in morphology and physiology between oaks and their competition (Kozlowski 1949, Wuenscher and Kozlowski 1971, Turner and Jones 1980, Parker and Pallardy 1988, Abrams 1990). Kolb and others (1990) examined the influence of limiting light, moisture, and nutrients on growth of northern red oak and yellow-poplar. They concluded that red oak was better adapted to moderately low resource levels and, following Grime's (1979) terminology, concluded that red oak has a "stress-tolerant" strategy of growth. Conversely, yellow-poplar has a "competitor strategy" in that it was better adapted to more productive environments, where rapid resource capture is critical for survival.

Morphological adaptations that account for the success of some oaks on xeric sites include deep roots, xeromorphic leaves, and an effective xylem transport system (Abrams 1990). The conservative seedling growth habit of most oaks that emphasizes root growth in the first few years probably imparts a survival benefit to oaks on xeric sites (Dickson and others 1990, Dickson 1991) as does the deep root system of older trees (Bourdeau 1954, Kozlowski 1971, Hinckley and others 1981). Oak leaves possess several traits, such as high stomatal density, thicker mesophyll, and smaller guard cells that may improve water use efficiency (Bidwell 1974, Abrams and Kubiske 1990). The ring-porous vascular system of oaks is composed of large diameter, early-wood vessels and narrower late-wood vessels (Zimmerman and Brown 1977). This anatomy permits rapid water movement when water is plentiful, and reduced but sustained movement during drought (Abrams 1990).

Numerous physiological characteristics of oaks may impart a survival benefit on dry-mesic or xeric sites. There may be large differences even between different oak species (Hinckley and others 1978, 1979; Reich and Hinckley 1980; Bahari and others 1985; Chambers and Henkel 1989; Abrams and others 1990), but oaks generally appear to be better adapted to droughty sites than co-occurring species. Abrams (1990) presented an excellent review of these physiological adaptations in oaks. As compared to co-occurring species, they include: (1) higher rates of photosynthesis and less decrease in photosynthesis with increasing soil and atmospheric drought, (2) higher water use efficiency, (3) slower stomatal closure as drought progresses and higher leaf conductance, (4) lower water potential for stomatal closure, and (5) greater osmotic and elastic adjustments in the leaves.

Oaks do occur, sometimes in almost pure stands, on mesic upland sites as well as on better bottomland sites. In light of the above discussions, it can be concluded that oaks are there because of a fortuitous set of circumstances created by nature or incidentally by acts of man (Aust and others 1987, Crow 1988), not by intentional management practices designed to obtain oak regeneration. For example, in essentially pure bottomland oak stands, we could document some form of disturbance, either fire, grazing or mowing, as instrumental in their establishment (Aust and others 1987). The lesson to be learned is that if we want to grow oaks on those sites we must create an environment that meets and favors the biological requirements of the oaks as opposed to the competing species.

ARTIFICIAL REGENERATION

Problems associated with artificially regenerating good sites are essentially the same as those encountered for natural regeneration at the time of final harvest and release, i.e., slow growth response of the small seedlings. In both cases there must be a balance between root and shoot growth, but with planted seedlings, rapid root growth is critical to maintain a balance between absorbing surface and transpiring surface (Parker 1949).

Early attempts at artificial regeneration of oaks, especially on upland sites, were not successful (Olson and Hooper 1968, McGee and Loftis 1986). Lack of success was probably related to quality of the planting stock (less than desirable size), and kind and amount of competition. More recent plantings of northern red oak have demonstrated that artificial regeneration can be successful on good sites in the Ozarks (Johnson 1984). Planting recommendations based on these results call for large planting stock (1-1 transplants) clipped about 15 cm above the root collar, establishment beneath a thinned stand (60 percent stocking), release by clearcutting 3 years later, and competition control at time of planting and at time of overstory removal. This technique should result in large, well established seedlings, with a large root system, that will respond well to release (Johnson 1984). The treatments seem to provide an environment that is compatible with the morphological adaptations and physiology of the species. Interestingly, these treatment recommendations are very similar to what recent research has shown may work well for natural regeneration (Janzen and Hodges 1987, Kruger and Reich 1989, Lockhart 1992).

SUMMARY AND SILVICULTURAL IMPLICATIONS

Acorn production, acorn losses, and poor initial seedling establishment can, in some cases, account for oak regeneration failures, but overall the major cause of failure on good sites seems to be a slow juvenile growth rate of oak seedlings and the inability to respond to release. The problem is one of competition—the inability of oaks to compete efficiently with more tolerant species, especially those in the lower canopies at low light levels, and with well established and/or faster-growing species under open conditions. The differences between species are the result of differences in morphology and physiology and the ability to acclimate to prevailing environmental conditions.

Figure 3 is an attempt to depict what is known about success of oak regeneration as influenced by site and competition with co-occurring species. Oaks are generally not very "flexible", i.e., they do not acclimate morphologically and physiologically well to changing environments, especially light. On good sites under a dense canopy oaks may undergo slight morphological and physiological acclimations, but these are insufficient to enable them to compete effectively with more tolerant species. Compared to such species, oaks have a higher light compensation point, are less efficient at use of "light flecks," have similar or lower rates of net photosynthesis, have higher rates of respiration, have slower stomatal opening and/or greater stomatal resistance, and have lower quantum yield. At the other extreme, these same oak seedlings may not compete well after release even in full sunlight. The poor competitive ability reflects physiological and morphological characteristics of the oaks. Photosynthesis may be saturated near one-third of full sunlight and rates of net photosynthesis are far less than for intolerant co-occurring species. Furthermore, carbohydrate allocation patterns in oak seedlings emphasize root growth rather than shoot growth. Intolerant competitors allocate more reserves to shoot growth, giving them a height advantage.

On drier mesic or xeric sites, oaks are in a better competitive position than on more mesic sites. This competitive position again reflects differences in morphology and physiology between the oaks and competing species. Morphological and anatomical characteristics of leaves and xylem, as well as carbon allocation patterns that favor root growth, result in better water-use efficiency and less, or delayed, moisture stress in the oaks. Less stress in turn means less reduction in physiological processes, such as photosynthesis, and therefore better growth.

This brief review of oak ecology and physiology helps explain why it is often difficult to obtain satisfactory regeneration of oaks. The major problems are competition with more tolerant and/or faster growing species and the "inflexible" nature of the growth habit of oaks. Oak regeneration efforts can be successful as long as ecological and physiological requirements are understood and an environment is created which favors those requirements.

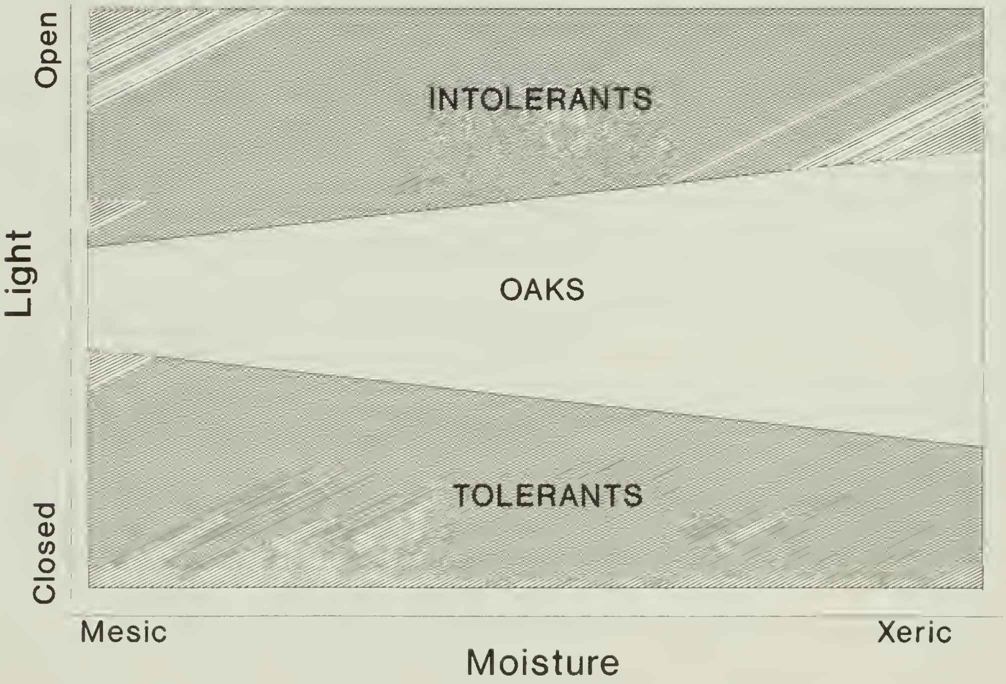

Figure 3—Conceptual representation of oak regeneration success over a range of moisture and light levels. Width of unshaded section indicates relative competitiveness of oaks with co-occurring tolerant and intolerant species.

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The Role of Fire in Oak Regeneration

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ABSTRACT

Fire has played a dominant role in sustaining oak forests. Oak species have biological adaptations, such as thick bark, a tenacious ability to resprout repeatedly following top-kill, and resistance to rot, which enable them, better than their competitors, to withstand a regime of frequent fire. Fire functions to encourage establishment of oak regeneration by: (1) creating favorable conditions for acorn caching by squirrels and bluejays, (2) reducing populations of insects which prey on acorns and young oak seedlings, (3) xerifying mesic sites through consumption of surface organic materials and exposure of the soil to greater solar radiation, and (4) reducing understory and midstory competition from fire-intolerant species. The ability of oaks to continually resprout when numbers of other sprouting hardwoods have been reduced by fire may allow oak to accumulate in the advance regeneration pool. Improved root/shoot ratios resulting from frequent top-kill should enhance response of oak seedling/sprouts to release and enable them to dominate when stand-level disturbances create conditions favorable for rapid growth. Based on biological adaptations of oak to fire, ecological functions of fire, and fire history, tentative guidelines are presented for using fire to promote oak regeneration on better sites. Effects of wildfires and intense fires in logging debris on establishment and development of oak-dominated stands are discussed.

INTRODUCTION

Oaks are often replaced by other species when mature stands are harvested, especially on better quality sites (Sander and others 1983, Loftis 1990, Abrams 1992). Even though researchers generally agree that fire played a role in the establishment of many oak-dominated stands at the turn of the century (Sander and others 1983, Crow 1988, Maslen 1989), there is relatively little research concerning the use of fire in oak ecosystems. Most of the forestry research about fire-oak relationships has dealt with the use of fire to control oaks in pine stands. However, many foresters and ecologists are now recognizing the importance of simulating the natural disturbance regime, which often included frequent fire, to maintain the species composition of certain ecosystems. The purpose of this paper is to (1) describe the role of fire in ecology of oak regeneration, and (2) present tentative guidelines for the silvicultural use of fire to regenerate oak.

THE ROLE OF FIRE IN THE ECOLOGY OF OAK REGENERATION

Adaptations of Oak to Fire

Fire has traditionally been used in forest management to control plant succession. It is well documented by literally dozens of studies that both dormant- and growing-season fires in pine stands will top-kill small hardwood stems, including oaks. Frequent burns will arrest the development of the hardwood understory, although most species continue to resprout for years. However, it is interesting that oaks have lower mortality rates than competing species in regimes of frequent fire. Waldrop and Lloyd (1991) reported that oak mortality rates after 26 years of biennial summer burning in mature pine stands in the Coastal Plain were still below 50 percent, whereas mortality rates of other woody species ranged from about 60 to 80 percent.

This tenacious ability of small oak rootstocks to resprout repeatedly following frequent top-kill is an important adaptation of oak to frequent fire regimes. This characteristic should enable oak to dominate the advance regeneration pool in areas where fire occurs at frequent intervals. In addition, continued top-killing should result in a more favorable root/shoot ratio and faster growth after release. Other biological adaptations, such as thick bark, resistance to rotting after scarring, and the suitability of fire-created seedbeds for acorn germination (Lorimer 1985) enhance the ability of oaks to survive on sites exposed to frequent fire. Martin (1989) suggests that bark thickness may be the single attribute that best characterizes a species' adaptation to fire. While bark thickness is undoubtedly of great importance to the survival of mature trees in regimes of frequent fire, it would seem that the ability of oak advance regeneration to outlast its competition would be the critical factor insuring that oak is a major component of the next stand (Van Lear 1990).

Functions of Fire in Oak Regeneration

Fire has numerous functions which benefit oak regeneration (table 1). Fire removes excessive litter buildup from the forest floor, thereby preparing a favorable seedbed. Areas of thin litter are preferred by squirrels and bluejays for acorn burial (Galford and others 1988). An important ecological finding is that jays collect and disperse only sound nuts (Darley-Hill and Johnson 1981, Deen and Hodges 1990), which implies that if these acorns escape predation they will result in well-established first-year seedlings. Seedlings from freshly germinated acorns are unable to emerge through a heavy litter cover. Germination and first-year survival are best when acorns are buried about 3 cm deep in the mineral soil (Sander and others 1983).

Although removal of thick litter may expedite the germination process by encouraging the caching of acorns by squirrels and jays, it is important that not all the humus layer be consumed. The humus layer keeps the surface of the soil porous, so that uncached acorns can more easily penetrate the soil, retains moisture, and provides support for the new seedling (Carvell and Tryon 1961). The intensity and severity of a prescribed burn will determine the amount of organic matter lost on a site (Wells 1979).

Fire helps to control insect predators of acorns and new seedlings. Martin and Mitchell (1981) illustrated how insect populations can be reduced or eliminated directly or indirectly by fire (table 2). Insect pests act as primary invaders, secondary invaders, parasites, or scavengers on or in acorns (Gibson 1972). Many of these insects spend all or part of their lives on the forest floor. Infestations, which can vary from year to year and even from tree to tree in some areas, are a major contributor to the oak regeneration problem (Marquis and others 1976).

Annually about 50 percent of the acorn crop in Ohio is destroyed by the larvae of *Curculio* weevils, acorn moths, and gall wasps. Other insects attack germinating acorns and oak seedlings. However, recent studies indicate that prescribed burning may reduce populations of oak insect pests when conducted under proper conditions and at the appropriate time in the insects' life cycle (Galford and others 1988). A reduction in insect predation would allow more acorns to be scattered and buried by jays and squirrels, thus enhancing the probability of successful germination, and also encourage subsequent seedling establishment. Burning may also reduce rodent habitat, eliminating another source of acorn predation (Hannah 1987).

Table 1—Functional roles of fire in the ecology of oak regeneration

Function	Reference
Prepare seedbed and encourage caching	Galford and others 1988, Sander and others 1983
Discourage acorn and seedling predators	Galford and others 1988, Martin and Mitchell 1981, Hannah 1987
Open understory and reduce fire-intolerant competitors	Crow 1988, Maslen 1989, Harmon 1984, Martin 1989, Van Lear and Waldrop 1989, Loftis 1990
Xerify sites	Crow 1988, Van Lear 1990
Allow oak to dominate advance regeneration pool	Little 1974, Van Lear and Waldrop 1983
Increase flammable fuels	Komarek 1965, Martin and others 1975

Table 2—Effects of fire on insects[1]

Direct Effects

FIRE	HEAT ---------> SMOKE	INSECTS	In litter, duff On understory vegetation Exposed on trees

Indirect Effects

FIRE	----->	ORGANIC MATTER VEGETATION NUTRIENTS	----->	INSECTS	
FIRE	----->	VEGETATION	----->	INSECT HABITAT	Grass & forbs Shrubs Trees

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[1] Martin and Mitchell (1981).

A regime of frequent burning over long periods of time creates an open stand in pine or hardwood stands. In hardwood stands, long-term burning tends to eliminate small understory stems outright and gradually reduces the midstory and overstory canopy through mortality resulting from fire wounds. Increased light reaching the forest floor in these open stands will maintain the vigor of oak advance regeneration. Loftis (1990) demonstrated that elimination of the subcanopy with herbicides encouraged development of advance regeneration of red oak in mature mixed hardwood stands in the Southern Appalachians. Long-term burning should create a stand structure similar to those created by injecting understory hardwoods with herbicides.

Severe or frequent fires xerify the surface of forest sites by consuming much of the forest floor and perhaps even organic matter in the mineral soil, as well as by exposing the site to greater solar radiation through canopy reduction (Van Lear 1990). Adequate advanced oak regeneration in the Southeast is generally found more often on xeric sites than on mesic sites (Sander 1988). Crow (1988) cited the lower frequency of fire in recent years as a major factor in the failure of oak to regenerate on better sites. Conversion of mesic sites to more xeric conditions by intense fires or by a long regime of low intensity fires could explain in large part the ability of oaks to dominate sites where more mesic species normally occur. Mesic sites may only have burned during cyclic periods of dry weather which have apparently occurred in the Southeast for millennia.

The absence of fire since the turn of the century has allowed species that are intolerant of fire to become established and grow to a size where they, because of thicker bark associated with age, can now resist fire. At greater than 5 cm (2 in.) d.b. h., yellow-poplar becomes almost as fire resistant as oaks (Maslen 1989). Mockernut and pignut hickories, scarlet oak, red maple, and blackgum are examples of such species that are often found on sites where fire has been long absent (Harmon 1984, Martin 1989).

Suppression of fire has allowed shrubby understory species to occupy drier sites where fire was once frequent and oak more dominant. In particular, rhododendron has dramatically increased its areal extent (Van Lear and Waldrop 1989, Martin 1989). Impenetrable thickets of ericaceous species, such as rhododendron, mountain laurel, and huckleberry, now often dominate midstories and understories of hardwood stands in the Southern Appalachians and prevent desirable hardwood regeneration from becoming established (Beck 1989). Fire would top-kill these species and, although they do sprout, new growth is slow and they would likely be relatively unsuccessful competitors of regenerating oaks.

Yellow-poplar produces an abundance of seed almost annually, and although the seed has low viability, many remain viable in the litter and duff layer for several years (Carvell and others 1955, Maslen 1989). Yellow-poplar seed germinate readily following burning (Shearin and others 1972). However, in a regime of frequent fire, small yellow-poplar seedlings would be killed and the reservoir of stored seed in the duff would be gradually depleted. Thus, frequent fires would control to a large degree this major competitor of oaks on high-quality sites.

Frequent fire functions to allow accumulation of oak in the advance regeneration pool. Nearly all hardwood species sprout in a regime of annual winter fire (Thor and Nichols 1974, Langdon 1981, Waldrop and others 1987). Hardwood sprouting is more vigorous following periodic winter burns because of greater carbohydrate reserves (Hodgkins 1958). Thor and Nichols (1974) noted that even with periodic and annual winter burning, oak stems tend to increase at the expense of competing hardwoods. After two periodic winter burns and eight annual winter burns, oak stems comprised 61 and 67 percent of the total stems, compared to 51 percent oak stems on the unburned plots.

Annual summer fires eventually eliminate all hardwood sprouts (Langdon 1981, Waldrop and others 1987). Biennial summer fires also gradually eliminate hardwood sprouts, but, as mentioned earlier, oak succumbs more slowly than many other species (figure 1). Oaks, in the absence of prolific root sprouters, such as sweetgum, would gradually dominate the advance regeneration pool in mature mixed hardwood stands because of the tenacity of their sprouting (Carvell and Tryon 1961, Waldrop and others 1987). Increases in the number of oak sprouts and, more importantly, the number of top-killed oak stems (up to 15-cm ground diameter) with basal sprouts following summer broadcast burns suggest that periodic summer burning would be expected to favor oak even more (Augspurger and others 1987).

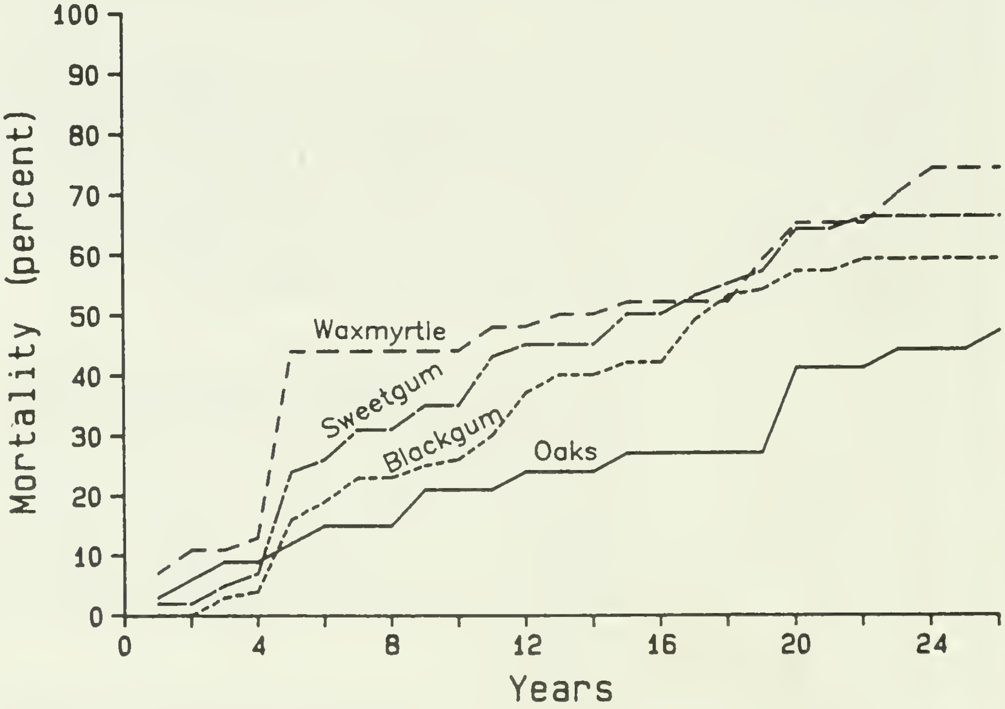

Figure 1—Cumulative mortality of hardwood roots over 26 years of biennial prescribed burning (Langdon 1981).

When repeated burning occurs in stands with mixed advanced regeneration, oaks have an advantage over less fire-resistant vegetation, which is killed by fewer fires of lower intensity (Waldrop and others 1987). This loss usually exceeds species gain through invasion, since the frequency of the fires is as important to reduction of fire-susceptible species as the intensity of the fire (De Selm and others 1990). Sander (1988) stated that effective hardwood competition control may require as many as three or more burns at 2- to 3-year intervals.

Studies of effects of single fires on composition of mixed stands have produced varied results. McGee (1979) found that single spring and fall burns in small sapling-sized mixed hardwood stands in northern Alabama had little effect on species composition other than to increase relative dominance of red maple and the number of multiple stem oak clumps. However, a single intense wildfire in a young mixed hardwood stand in West Virginia shifted species composition to a predominately oak stand (Carvell and Maxey 1969).

Frequent fire in oak stands may also increase the production of legumes and grasses, which benefit numerous wildlife species, but which also create a more flammable understory. At the turn of the century, summer fires were quite common in the Southeastern United States as farmers burned the land to facilitate grazing. They had learned from early settlers, who in turn had learned from their Indian predecessors, that growing-season fires best maintained an open forest with a rich herbaceous layer (Komarek 1965). Thor and Nichols (1974) noted an increase in herbaceous vegetation following frequent burning in mixed hardwood stands in Tennessee. Similar findings have been reported in pine forests of the Southeast by numerous researchers. Therefore, a burning regime of frequent fire functions to create and maintain a ground cover that encourages the return of fire, which for the reasons stated above would favor the establishment of oak advance regeneration.

SILVICULTURAL USE OF FIRE IN OAK REGENERATION

While some new oak stands result from stump sprouts, there is little dispute among silviculturists that oak advance regeneration is often critical to the re-establishment of many oak-dominated stands (Clark and Watt 1971, Sander and others 1983, Loftis 1988, Lorimer 1989). However, while many acknowledge that fire may have played a role in creating the present mature oak stands, no guidelines have been developed for using fire to regenerate oak stands.

Based on the history of fire in the southeastern United States, and on biological adaptations of oak and ecological functions of fire discussed earlier, the following *tentative* guidelines are suggested for using fire in oak management. Our hypothesis is that silviculture which mimics the disturbance regime that created present-day stands dominated by mature oak will create future stands dominated by oak. Further research will be necessary to test and fine-tune these suggestions before they can be recommended as silvicultural practices.

To Promote Advance Regeneration

It has been suggested (Little 1974, Sander 1988, Van Lear and Waldrop 1989) that an extended period of repeated burns prior to harvest may improve the status of oak in the advance regeneration pool, especially on better sites. Although figure 2 depicts the sequence of suggested actions and likely responses to fire, there is no research that currently documents a series of burning treatments that will successfully accomplish this goal. Therefore, a burning regime might include a mix of winter and summer fires adjusted to enhance the relative position of oak in the advance regeneration pool.

The famous Santee Fire Plot study showed that annual summer burns for 5 years in a pine stand in the Coastal Plain killed about 40 percent of oak root stocks compared to 55 to 90 percent of other woody competitors (Waldrop and others

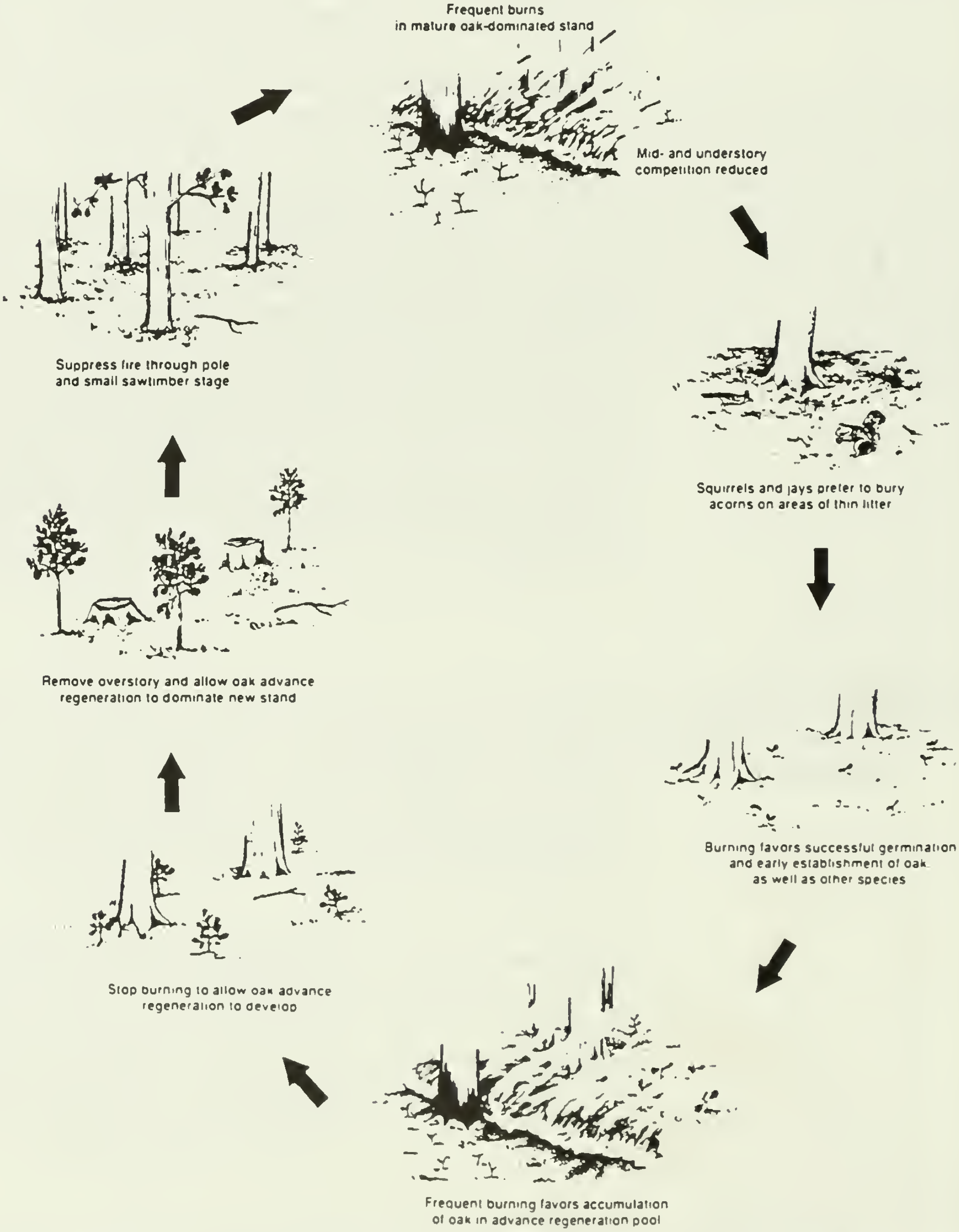

Figure 2—Tentative scenario of using prescribed fire to encourage advance reproduction of oak.

1987, Waldrop and Lloyd 1991). Biennial summer burning killed hardwood root stocks more slowly, but the rate of mortality for other woody species was still significantly greater than that of oak species. Annual winter burning, while not as effective as summer burning in altering species composition, still tends to xerify the site by consuming litter and reducing shading of top-killed understory species.

Initial height growth of oak advance regeneration is slow, since most of the early growth goes into the root system (Kelty 1988). Burning can increase the average annual shoot growth of oak seedlings, providing a potential advantage over competing stems (Johnson 1974). Oak advanced regeneration occurs as true seedlings or sprouts; the latter have root systems older than the stems and are often referred to as seedling-sprouts (Sander and others 1976). A large root system is necessary for initiation of shoot growth when environmental conditions become favorable (Crow 1988). Thus, a regime of frequent understory burns, perhaps including both growing-season and winter burns during a period of 5 to 20 years prior to harvest, should promote a favorable root/shoot ratio during oak seedling establishment. The timing of the burns would be dependent on the observed vigor of the oak advance regeneration and its competitors.

Once an adequate number of oak seedling-sprouts are present and numbers of competing species have been sufficiently reduced, fire should be withheld to allow the oak advance regeneration to attain sufficient size to outgrow other species which germinate or sprout after the mature stand is cut. A relatively open stand with few midstory and understory trees would provide adequate light for the oak advance regeneration to develop into stems of sufficient size to outgrow other species after the overstory is removed. Sander and others (1983) recommend that 1,075 advance regeneration oak stems/ha over 1.5 m tall be present before the overstory is removed.

Herbicides may be required to remove midstory trees that have grown too large to be killed by low-intensity fires. Loftis (1988, 1990) has convincingly shown that growth of advance regeneration of northern red oak can be enhanced by herbicidal removal of midstory and understory competitors. Herbicides provide initial selectivity of midstory stems to be eliminated prior to burning. A combination of herbicide treatment and frequent fire may be required to secure oak regeneration and allow it to maintain its vigor in mixed hardwood forests which have not been burned for decades.

Although methods have been developed to predict fire-induced mortality of large trees based on stem size and extent of fire damage (Loomis 1973), research is needed to determine if and how prescribed fire can be used without excessive damage to stems of large valuable crop trees in mature hardwood stands. It should be understood that the prescribed fire regime being suggested here is for use of fire only during the regeneration period. In this case, if rot should develop in damaged trees, it will have a relatively short time to grow and damage butt-log quality.

Foresters have long recognized that wildfire is a major cause of butt rot in hardwoods, but relatively little information is available concerning the relationship between prescribed fires and stem damage. Wendel and Smith (1986) found that a strip-head fire in the spring in an oak-hickory stand in West Virginia caused a decline in overstory vigor and resulted in death of many trees during the 5 years after burning. However, a low-intensity winter fire in a mixed hardwood stand in the Southern Appalachians resulted in little or no cambium damage to large crop trees (Sanders and others 1987). More research is needed to determine the extent of bole damage from prescribed fire in different seasons and under varying frequencies in mature hardwood stands.

It must be emphasized that a series of burns over an indefinite preharvest period will likely be required to favor oak regeneration. The first burn may be detrimental to oak advance regeneration in that small rootstocks may be killed. However, our interpretation of the literature suggests that, over the long-run, oak will be less adversely affected than competitors and will therefore receive a competitive advantage that will enable them to favorably respond to subsequent release.

To Increase Quality and Numbers of Oak Stems after Clearcutting

Vigorous, abundant sprouting of oaks occurs following broadcast burning of clearcut areas. Burning of clearcut hardwood or mixed pine-hardwood stands promotes better quality oak sprouts by forcing them to develop from the groundline. Over 97 percent of all oak sprouts developing after broadcast burning of logging slash in the Southern Appalachians were basal sprouts, versus 71 percent for unburned areas (Augspurger and others 1987). Suppressed buds higher on the stump are apparently destroyed by the intense heat of the fire. Sprouting from buds at or below groundline is encouraged by fire, reducing the likelihood of rot being transferred from stumps to new sprouts (Roth and others 1939). Poorly formed tops of small (< 15 cm) oak stems killed by fire are replaced by more desirable sprouts, which are more likely to develop into sound timber trees than other types of oak regeneration (Roth and Hepting 1943, Teuke and Van Lear 1982).

Some research suggests that fire may cause multiple sprouting from top-killed advance regeneration (McGee 1979). In addition, some rootstock may be damaged or even consumed by fire, thereby reducing the regeneration potential of the stand. Many questions remain unanswered regarding the effects of broadcast burning on stem quality of regenerating oak stems. However, observations of dozens of hardwood-pine stands regenerated using the "fell and burn" site preparation technique (Abercrombie and Sims 1986) suggests that broadcast burning under carefully prescribed conditions is favorable to quality oak regeneration in the Southern Appalachians.

Intense fires can sometimes result in the introduction of oak in the succeeding stand. Nowacki (1988) documented cases in northern Wisconsin where clearcutting of old-growth maple-hemlock stands and slash burning resulted in even-aged stands dominated by northern red oak. Lorimer (1989) suggested that these oak stands probably developed from acorns brought into the burned area by birds and animals. Similar observations have been made following an intense wildfire in the mountains of South Carolina.

CONCLUSIONS

Oaks in the Southeast are being replaced by other species on better sites where oaks were once dominant. The fire history of this region, biological adaptations of oak and other species to fire, and ecological functions of fire in oak ecosystems strongly suggest that oak replacement on these better sites is largely the result of a fire regime different from that which existed in the region in previous millennia. Until the past half century, frequent fires apparently allowed oak regeneration to accumulate and develop in the open understory of mature stands at the expense of shade-tolerant, fire-intolerant species. When the overstory of these stands was either completely or partially removed by various agents (wind, insects, wildfire, Indian clearing, harvesting, etc.), conditions were created which allowed advance regeneration dominated by oak to develop into mature stands dominated by oak.

If oaks are to be maintained as a dominant overstory species on good quality sites in the Southeast, foresters will have to either restore fire to some semblance of its historical role as a major environmental factor or develop methods that simulate the effects of fire. It will be essential for foresters, as well as the public, to recognize that fire was a major factor shaping the composition and structure of many forest ecosystems.

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Flowering and Oak Regeneration

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ABSTRACT Episodic acorn production appears to be the norm for the genus *Quercus*. This year-to-year variation has been associated with the number of pistillate flowers, the supply of pollen, weather, insects, nutrition, and genetics. Acorns are the fruit of the oak tree, developing from the pistillate flower. Depending upon successful pollination and fertilization by pollen produced in the staminate flowers, one of six ovules will survive and grow; the other five will abort. We usually notice the tiny pistillate flower after fertilization when the cupule and pericarp start to enlarge and begin to look like an acorn. This is also about the time when acorn weevils begin to oviposit. It is a long, arduous journey from the emergence of the flowers in the spring to their maturation as acorns. The appearance of abundant pistillate flowers does not guarantee a successful acorn crop. Can we predict an acorn crop prior to a few weeks before seedfall? Not reliably. Can we predict the appearance of a flower crop? Not yet, and not before we understand clearly how biotic and abiotic factors affect flower initiation and development in individual species.

When the subject of "flowering" in oaks arises, we tend to think about acorn production. Although these are two different topics, they are part of the continuum where flowering leads to acorn production. This paper dissects that continuum into component processes such as flower initiation, flower development, and embryology, in the context of addressing the following questions:

1. What should a forester know about flowering?
2. What factors affect flowering?
3. What is the relationship between flowers and acorns?
4. Can we predict flower crops?

WHAT A FORESTER SHOULD KNOW ABOUT FLOWERING

Pistillate Flowers

The oak pistillate flower begins its journey to becoming an acorn when the meristematic tissues of the bud receive a signal, the as yet unknown flowering stimulus, that directs axillary primordia in some of the leaves to become an inflorescence stalk and not a vegetative bud (Minina 1954, Turkel and others 1955, Romashov 1957, Merkle and others 1980). These researchers could not differentiate the stalk from the bud until late summer when bud scales began to arch over the vegetative bud primordium. In contrast, the inflorescence primordia remain relatively naked, having only one or two bracts (Merkle and others 1980), and may be somewhat larger than the vegetative bud (Turkel and others 1955). The conclusions of Turkel and others (1955) and Merkle and others (1980) are based on microscopic observation of prepared specimens of *Quercus alba* (table 1).

Table 1—Species of *Quercus* discussed in this paper

Latin names	Common names
North American	
Q. alba L.	White oak
coccinea Muenchh.	Scarlet oak
gambelii Nutt.	Gambel oak
ilicifolia Wangenh.	Bear oak
prinus L.	Chestnut oak
rubra L.	Northern red oak
velutina Lam.	Black oak
European and Asian	
Q. aegilops L.	
ilex L.	
macrolepis Ky. (Probably a subspecies of *Q. aegilops)*	
myrsinaefolia Blume	
petraea (Mattushka) Lieblein (Includes *Q. sessiliflora)*	
pubescens W.	
robur L. (Includes *Q. pedunculata)*	
trojana Webb	

Minina (1954) and Romashov (1957), viewing fresh material of *Q. robur* under a dissecting microscope, could not identify the inflorescence primordia until late winter or early spring. Bonnet-Masimbert (1978) could not identify the flowers of *Q. pedunculata (robur)* or *Q. sessiliflora (petraea)* during the winter.

Pistillate inflorescence development in *Q. alba* resumes in late March (Merkle and others 1980). The axis begins to elongate and several additional bracts are produced in a spiral. In the axil of each bract a pistillate flower begins to differentiate, but, in general only the lower ones became functional. There are usually 2-3 functional flowers, with a range of from 1-5. In *Q. rubra*, pistillate flowers form in the axils of two lower, opposite bracts, and occasionally only one is formed (Sattler 1973).

The ontogeny or sequence of development of the oak flower parts from the floral apex of *Q. rubra* was described in detail by Langdon (1939) and Sattler (1973). Six perianth primordia are initiated, three outer and then three inner. These primordia are elevated by meristematic activity beneath them. Three gynoecial (carpel) primordia appear on the apex opposite the three outer perianth primordia and they grow together laterally to eventually become the stigmas. As growth continues upward, the area beneath becomes the ovary wall. Conrad (1900) observed that carpels are already evident in winter buds of *Q. velutina*. Thus, there may be much variation between species in the same subgenus.

The young ovary closes as the gynoecial primordia are carried up with the ovary wall. Concurrently, the growth between and at the base of the gynoecial primordia initiates the septa. Three septa are formed and become appressed at their upper, inner margins; they are not joined at their base. Two placentae form initially as slight protrusions along the base and on each side of the septa. Thus, in each locule there are two placentae—one from each septum. When the ovary cavity of *Q. myrsinaefolia* is closed, the upper portion remains uniloculate, having three separate septal protrusions, but is triloculate at the basal region (Okamoto 1982).

The ovule of *Q. rubra* develops as a further enlargement of the placental bulge, but the timing in relation to anthesis is unknown (Sattler 1973). Okamoto (1982) found that the ovules of *Q. myrsinaefolia* are not initiated at anthesis, while Turkel and others (1955) found that ovule development begins at that time. However, the timing of ovule development in the erythrobalanus (red oak) subgenus may differ from the lepidobalanus (white oak) subgenus.

What is an ovule? Botanically speaking, an ovule is a megasporangium; i.e., a structure that bears the megaspore mother cell (MMC) (Davis 1966). The MMC undergoes meiosis or reduction-division, producing four haploid cells, only one of which survives to become the functional megaspore. By a series of mitotic divisions the megaspore gives rise to the megagametophyte or embryo sac, an eight-nucleate structure at the tip of the nucellus. The nucellus is partly covered by the inner and outer integuments. When the integuments have elongated over the end of the nucellus, the "hole" that is formed is called the micropyle. This is the route through which the pollen tube approaches the embryo sac (Benson 1894). Major food reserves of starch and lipids are located almost exclusively within the outer integument, while the inner integument is virtually void of food reserves (Mogensen 1973). Mogensen proposed that the pathway for food materials in the ovule is from the outer integument to the chalaza (basal portion of the ovule) and then through the postament (central core) of the embryo sac.

The study of embryo sac formation in plants has received much attention from botanists. Conrad's (1900) study of *Q. velutina* is considered the initial study of this structure in the genus *Quercus*. That study briefly described the pattern of nuclear division that yields an eight-nucleate embryo sac at the tip of the nucellus. It was 50 years before the next papers on embryo sac development appeared. These included investigations of *Q. macrolepis* (Bagda 1948, 1952), *Q. robur* (Hjelmqvist 1953), *Q. alba* (Turkel and others 1955), *Q. ilex* (Corti 1959), *Q. aegilops* (Scaramuzzi 1960), and *Q. trojana* (Bianco 1961).

Once the embryo sac is formed, fertilization of its egg and central cell via germinating pollen must occur for seed development to continue. Unfortunately, the details of pollen tube growth through the stigma and stylar tissues are not documented for any species of *Quercus*. Some observations suggest that pollen tube growth does not proceed for several weeks after the pollen grains land on the stigmatic surface and that pollen germination waits for the ovule to complete development (Jovanovic and Tukovic 1975). Notwithstanding, Mogensen (1972) provided the only detailed evidence of pollen tube invasion through the micropyle and into the egg apparatus of the embryo sac of *Q. gambelii*. Upon reaching the embryo sac, the branched pollen tube grows along one of the synergids and penetrates it by growing through the filiform apparatus. The pollen tube opens at its tip and releases its contents. Although fertilization occurred, Mogensen (1972) did not observe the isolated male gametes or their union with the egg nucleus or the central cell.

Following fertilization, a free-nuclear endosperm grows before the first division of the zygote occurs (Hjelmqvist 1953, 1957; Brown and Mogensen 1972). In general, as the endosperm becomes cellular, the embryo begins to differentiate (Singh and Mogensen 1976), moving quickly through the heart-shaped stage. Singh and Mogensen (1976) concluded that the endosperm does not have a major function as a food storage tissue, but rather may serve as a translocating tissue to the embryo. During zygote and early embryo stages, lipids may be more important as a nutrient source, while starch is probably utilized at later stages of embryo development (Singh and Mogensen 1975).

Information about embryo and cotyledon growth is very limited. Mogensen (1965) provided the most detailed picture in his comparative study of *Q. alba* and *Q. velutina*. One major difference he noted was that the epicotyl apex of *Q. alba* produced from three to five leaf primordia prior to acorn maturity, while *Q. velutina* produced none. Stairs (1964) also found no leaf primordia in mature embryos of *Q. coccinea*. Cecich (unpubl. data) found large concentrations of druse crystals in cotyledons of *Q. velutina* and *Q. rubra*, but none in *Q. alba*. The relative unpalatability of erythrobalanus acorns, considered to be related to increased content of lipids and tannins (Goodrum and others 1971, Short 1976, Smallwood and Peters 1986, Smith and Follmer 1972), may also be related to irritations caused by these large crystals.

It is difficult to provide a generalized calendar of events from ovary development through acorn maturation. Variation among and within species, geographic location, weather conditions, and sampling problems would make the results of that task questionable. Merkle and others (1980) provided an example of this variation when they compared their observations of *Q. alba* ontogeny with those of Turkel and others (1955). Nevertheless, the time of pollen shed is probably the best local index for the beginning of the seed production cycle but, does not include flower initiation and development within the bud. In the lepidobalanus group the pollen tube fertilizes the egg about 4-6 weeks after initiating growth. Variation in the time of embryo growth and maturation of the acorn occurs and, depending upon species, acorns drop over a several-month period (USDA 1974).

Staminate Flowers

The first sign of differentiation of the staminate inflorescence primordium ranged from late May (Merkle and others 1980) and early June (Turkel and others 1955) in *Q. alba* to June and July in *Q. robur* and *Q. petraea* (Minina 1954, Romashov 1957, Jovanovic and Tucovic 1975). Similar observations are not available for species in the erythrobalanus subgenus.

The inflorescence, which is inserted in the axil of a bud scale and not a leaf (Minina 1954), is without appendages until late June or early July, when meristematic areas appear on the axis (Merkle and others 1980). These floral apex primordia appear before or coincident with the subtending bract primordia (Turkel and others 1955). However, Sattler (1973) found that the floral apex of *Q. rubra* is initiated in the axil of the bract, just the opposite of *Q. alba*.

On the flank of each floral apex, the perianth primordia appear, fusing into a single perianth as they grow. The stamen primordia appear on the apex opposite the perianth members in mid to late July. By fall, these stamen primordia grow into immature anthers and filaments. The overwintering condition of the slightly-lobed anther is that of a homogeneous parenchymatous mass (Turkel and others 1955).

Resumption of anther development in the spring varies by species and location: early March (Bonnet-Masimbert 1984), late March (Merkle and others 1980), April (Turkel and others 1955), and mid to late April (Conrad 1900). The parenchymatous mass differentiates into the sporogenous mass and the parietal layers. The number of sporogenous cells increases mitotically and eventually become the microspore mother cells which undergo meiosis to become microspores and, finally, pollen grains. Stairs (1964) has provided the only account of meiosis in *Quercus*. During the meiotic process, the parietal layers differentiate into the tapetum and the anther wall. Dehiscence of pollen grains occurs about 6 weeks after resumption begins (Turkel and others 1955). Before leafing out, the staminate inflorescence, bearing numerous staminate flowers, elongates and emerges from the bud scales as the familiar catkin (Vogt 1969).

There are conflicting observations about the dynamics of pollen tube growth after the pollen lands on the stigmatic surface. For instance, pollen germination in *Q. robur* was completed within 24 hours, but fertilization occurred 6-7 weeks later (Jovanovic and Tukovic 1975). Benson (1984) didn't find pollen tubes in *Q. robur* until just before fertilization. In contrast, Allard (1932) observed that: "When pollen reaches the stigma of members of the white oak group, the growth of the pollen tube containing the male cells follows an uninterrupted advance into the tissues of the style until the ovules are fertilized." These two extremes of pollen tube behavior for members of the same subgenus suggest that we should investigate this anomaly to better understand the among-species variation. Allard also found that in the red oak group the pollen tubes cease growth at the base of the style until the following spring when fertilization of the ovules occurs.

Pollen tube growth may also be affected by temperature. Pollen of *Q. pubescens* requires a higher temperature for germination (38 °C) than *Q. robur* (20 °C). Low and erratic fertility of *Q. pubescens* in cold habitats may be attributed to the prevention of pollen germination. This temperature limit may also explain the northern boundary for the species range (Jicinska and Koncalava 1978).

Flower Distribution

The distribution of various bud types on a branch has been in *Q. robur* and *Q. petraea* (Minina 1954; Romashov 1957; Bonnet-Masimbert 1978, 1984). Minina and Romashov described five types of buds: simple male, male and vegetative mixed, female and vegetative mixed, complex (male, female, and vegetative), and vegetative only (active or dormant). Bonnet-Masimbert recognized six types: vegetative, vegetative and male, male only (rare, but occur in years of heavy flowering), vegetative and female, vegetative and hermaphroditic (not the same as Minina's complex type). Bonnet-Masimbert's sixth type is the latent bud which Minina puts under the vegetative category. Buds containing uncommitted primordia were considered important in reconstituting a branch system after insect attack.

Many researchers of oak reproductive biology have concluded that flowering is irregular from year to year without mentioning the variation in distribution of bud types. Bonnet-Masimbert determined that a large acorn crop is related to a large number of male flower buds, manifested through an increase in hermaphroditic buds and, to a lesser extent, to the number of female flowers. When the acorn crop was poor, large numbers of buds in the potentially male zone on a branch did not evolve.

Schlarbaum and Rhea (unpubl. data) evaluated flowering in a 17-year-old *Q. rubra* seedling seed orchard in Tennessee. They selected a light-, medium-, and heavy-flowering tree and counted all pistillate flowers. The majority of flowers were located in the upper one third of the crown of each tree, and there were no differences in flower numbers among the quadrants in a crown. Similarly, Jovanovic and Tukovic (1975) cited observations by Rempe (1937) and Piatnitsky (1954) that the greatest quantity of pollen was produced in the upper part of the crown. Sharp and Chisman (1961), however, found that pollen catkins were evenly distributed across the crown of *Q. alba*. I have also observed the latter in *Q. alba*, *Q. rubra*, and *Q. velutina*.

FACTORS AFFECTING FLOWERING

Phase Change and Flowering

One of the difficulties in forest tree breeding and flowering research is the long time between generations. Most oaks take 15 to 25 years to reach minimum seed-bearing age (USDA 1974). Reducing that time would reduce the length of a generation cycle and make it possible to increase genetic gain-per-unit-time by making earlier selections (Lambeth 1980). If earlier flowering can be attained in oak species, it would be possible to generate inbred lines, whose usefulness has been demonstrated in many crops. Inbreeding not only increases heritability and facilitates selection, but it also helps to reduce the "genetic noise" common to physiology research. Although inbreeding has been successfully demonstrated in *Quercus* (Irgens-Moller 1955), Jovanovic and others (1971) did not get successful embryo development in self-pollinated oak flowers.

It is generally accepted that the change from a juvenile to a mature state (Poethig 1990) in forest trees occurs at the time of first flowering (Zimmerman 1972). A juvenile tree is not capable of flowering because it is not able to respond to stimuli that would otherwise induce flowering; while a mature tree may not flower because of the absence of the stimuli or genetic control causing sterility. Thus, the onset of flower production is used as an indicator that the juvenile phase has ended and that the mature phase has begun (Wareing 1959).

How do you get a tree to pass from the juvenile to the mature phase sooner? A common strategy is to grow seedlings in an environment that greatly increases growth rate. Some of the cultural methods used to do this include elevated temperatures, long photoperiods, adequate water, and fertilization. Thus, size *per se* is positively correlated with early flowering.

The inheritance of early flowering in forest trees has been demonstrated in *Betula verrucosa* (Johnsson 1949) and in *Pinus sylvestris* (Teich and Holst 1969). A dominant major gene has been implicated in controlling early flowering in both species. Because early flowering is inherited, selection pressure can be applied to increase the frequency of progenies that flower early. In jack pine (*Pinus* *banksiana* Lamb.) the larger trees in a family are more likely to flower first (1 year from seed) (Bolstad and others 1991). Once again, the size of the tree is positively correlated with the attainment of early flowering.

An alternative to waiting for seedling-origin plants to produce flowers is to use sprouts. Wolgast and Stout (1977) used sprouts in clearcuts to determine the earliest age at which acorns of *Q. ilicifolia* could be produced. Pistillate flowers appeared on sprouts at the beginning of the second growing season, indicating that flower primordia were initiated during the first season. Acorns were mature at the end of the third season. Sharik and others (1983) also found that stems of coppice-origin *Q. prinus* first produced acorns in the third season, compared to 20 years for seedlings. Advance reproduction seedlings and seedling-sprouts of the same age produced no acorns.

Components of the Flowering Process

There are three major components to the flowering process in oaks: (1) Initiation, (2) Differentiation of the staminate and pistillate inflorescences and their flower primordia, and (3) Emergence of the flowers, receptivity of the stigmas, and shedding of pollen. Let us examine how various factors may affect these components.

Initiation refers to how chemical, genetic, and abiotic factors interact during a critical time period to cause a cell or meristem to commit itself to become a flower or flower part. This is not the same as differentiation wherein the structural manifestation of the initiation process occurs; e.g., the appearance of the staminate inflorescence in late May (Merkle and others 1980). Most of what we know about flower initiation is based on research with annual plants (Evans 1969, Bernier 1988). However, woody plants behave differently. They have long juvenile periods during which they do not flower, even though the proper environmental stimuli may be present. In addition, annuals tend to have terminal flowers, that is, the shoot apical meristem *per se* becomes a flower. In woody plants, which must grow year after year, the flowers are normally axillary. One way of defining the period of flower initiation in conifers is through the use of plant growth regulators, primarily the gibberellin $A_{4/7}$ mixture ($GA_{4/7}$) (Owens and Blake 1985). Unfortunately, GAs rarely induce flowering in hardwoods and there is no known method for reliably doing so. This includes the application of mineral fertilizers, which have no apparent direct effect on flowering, although there may be an indirect effect from a correlated increase in crown vigor. Wolgast and Stout (1977) did note a positive fertilizer response in *Q. ilicifolia*. Any speculation about how a factor may be related to flower initiation must be accompanied by a notation of timeliness; i.e., during what specific time period does that factor operate. That notation does not now exist and so the discussion of flower initiation becomes almost fruitless (no pun intended).

Differentiation of reproductive structures many extend from late May (Merkle and others 1980) to the time of pollen shed and female receptivity about 1 year later. So how does one realistically ascribe the success or failure of the development of a flower crop over that length of time to factors such as weather? Except for deep freezes in late spring (Sharp 1958, Sharp and Sprague 1967, Goodrum and others 1971, Wolgast and Trout 1979), does the weather affect differentiation? Sharp and

Chisman (1961) found that *Q. alba* on 10 sites produced good-to-heavy pollen crops each year and that varying numbers of pistillate flowers were produced. Since staminate flowers were produced abundantly each year, did any factor inhibit their development during that year of differentiation? If a pistillate flower crop in a given spring is rated as poor, was it caused by biotic or abiotic factors during development or were the flower primordia ever initiated? Sharp and Sprague (1967) speculated that a warm late April and cool early May were related to early catkin emergence and delayed pollen dispersal, respectively. Under that weather scenario, pollen shed and pistillate flower receptivity were considered to be more closely aligned. They provided no anatomical observations to confirm their speculations.

Genetic control over seed production in oaks has been demonstrated by a number of investigators. However, Farmer (1981) found that in a given year seed production among clones of northern red oak was most highly correlated with the percentage of pistillate flowers that were fertilized, while year-to-year differences were associated with variation in the number of flowers. He believed that fecundity could be increased by selecting high-yielding clones in a grafted orchard. Ledig and others (1971) and Wright (1953) also found much tree-to-tree variation in reproductive ability. Grafting of oak scions selected from mature, flowering individuals can be readily accomplished and, thus, flowers can be made quickly available (Irgens-Moller 1955).

Floral sex ratios in *Q. ilicifolia* changed with position of the tree on a slope (Aizen and Kenigsten 1990). At the top of the slope tall stems had most of the male flowers. While at the bottom of the slope, there was no height relationship but there were fewer male flowers on all trees than there were pistillate flowers. The authors could speculate only that a change in temperature along the gradient influenced the physiological basis for sex allocation. Only stems at the top of the slope had second-year acorns, perhaps related to the increase in pollen availability at the top.

Emergence, Receptivity, and Shedding. Emergence of the staminate inflorescence and shedding of pollen are known to increase or hasten with rising temperatures and to drop with decreasing temperature (Romashov 1957). Rainy weather, associated with decreased temperature, also reduced pollen dispersal. The success of the acorn crop has not always been related to pollen dispersal. Sharp and Chisman (1961) concluded that pollen dispersal occurred when relative humidity dropped and remained below 45 percent for several hours, but they did not mention the success of the acorn crop. Similarly, Jovanovic and Tukovic (1975) cited European literature indicating that pollen grains separated better when relative humidity was lowest.

Wolgast (1972) explored the effect of relative humidity experimentally. In a series of growth chamber experiments using *Q. ilicifolia*, he demonstrated that relative humidity at the time of pollen shed and stigma receptivity can limit the size of an acorn crop. No acorns matured when relative humidity exceeded 61 percent, but about half the flowers matured into acorns when relative humidity was lower. While hot, dry winds in early May caused dessication of pollen catkins, Sharp and

Sprague (1967) found no correlation with relative humidity and acorn yields in field studies and concluded that temperature was a primary factor in acorn crops.

Probably the most important factor controlling the emergence of pistillate flowers and their receptivity is temperature, which directly or indirectly influences flower emergence through branch and leaf elongation. Low air temperatures were associated with a delay in development of pistillate inflorescences of *Q. robur* near Moscow (Minina 1954). However, Goodrum and others (1971) concluded that the influence of low temperatures on flowering, setting of fruit, and subsequent acorn yield was inconclusive. Sharp (1958) also concluded that low temperatures in the spring did not affect flowering unless there was a freeze sufficient to damage shoots and leaves.

RELATIONSHIP BETWEEN FLOWERS AND ACORNS

Given that staminate and pistillate flowers have been initiated, differentiation completed, and pollen shed on the receptive stigma, what factors then affect how the pollinated pistillate flowers develop into acorns?

Until now I have presented information about oak flowering in a positive context; i.e., how the primordium originates and develops into a flower. But we also need to look at subsequent events in a somewhat negative context; i.e., how various factors may lead to the abortion of flowers or ovules and, thus, reduce the size of a potential seed crop. Several authors have concluded that the size of an acorn crop is not related to the size of a flower crop. The appearance of numerous pistillate flowers in the spring does not guarantee numerous acorns (Sharp 1958, Sharp and Chisman 1961, Wright 1953, Gysel 1956, Cecich and others 1991). What then are the factors or events related to the loss of the flowers? How are these factors and their timing related to the developmental chronology of the pollinated flower as discussed earlier? Information for answering these questions is limited.

Kossuth (1974) concluded that abscissions occurring during the first 11 weeks after anthesis in *Q. alba* were probably determined at or before receptivity by degeneration of the ovary. Although ovules had just differentiated at the time of receptivity, ovule growth did not appear to influence premature acorn abscission before or after anthesis. She confirmed the observations of Turkel and others (1955) that an abscission layer begins to form during anthesis between the ovary wall and the receptacle (cupule), and considered this to be an abscission layer analagous to that of a leaf petiole. It is my opinion that this abscission layer is simply the beginning of the separation of the seed coat (pericarp) and cupule manifested in a mature acorn.

Kossuth (1974) noted certain developmental thresholds associated with flower abortion. If ovules developed normally through anthesis, the first threshold was passed and development continued. The failure of megasporogenesis in all ovules of a flower seemed to be determined by anthesis, but abscission was not immediate. A second threshold following fertilization was related to the growth of the functional ovule. Most embryo abortion occurred before the cotyledons were one-third their final size. After a series of leaf size and photosynthesis measurements, Kossuth concluded that expanding leaves were associated with acorn retention and that leaves and developing flowers were not competitive sinks for assimilates. By the time of pistillate flower receptivity, the half-grown leaves were net photosynthesizers.

Kossuth's observations of flower survival and abortion agree with other studies, such as Williamson (1966), who found that about 90 percent of the premature flower abscissions occurred by the time of fertilization, Kossuth's second threshold. My observations of flower abortion in *Q. alba* agree with this. Fertilization in *Q. alba* in mid-Missouri occurs during late June, as noted by the presence of an endosperm in the embryo sac. By the first week of July a cellular endosperm and embryo are present (unpublished data). In 4 consecutive years, the percentage of flowers aborted by the first week of July was 98, 76, 83, and 90 percent, respectively. The number of maturing acorns per year, as a percent of the initial flowers, ranged from 0 to 6 percent. Clearly, most of the potential acorn crop is lost by the time of fertilization. Late-spring freezes can also kill second-year pistillate flowers in the erythrobalanus group and prevent them from maturing into acorns (Wolgast and Trout 1979). The impact of drought on either differentiation of flowers or on developing acorns is inconclusive (Sharp and Sprague 1967). Fungi probably have no effect on fertilization success, even though they are widely found on stigmas (Kolpak and others 1980).

The literature suggests that the abortive ovule of *Quercus* develops a normal embryo sac, fertilization occurs, and a zygote or proembryo stage may be reached (Stairs 1964, Mogensen 1965). However, Mogensen (1975) showed that there are several possible pathways for abortion, even within the same ovary. In observing *Q. gambelii* he found that fertilization to the normal embryo sac failed to occur 45 percent of the time. Ovule abortion caused by failure of the zygote or embryo accounted for 28 percent of the ovules. In 26 percent of the ovules examined, an embryo sac failed to develop within the nucellus. Occasionally, embryo sacs were found without any cellular contents, but these could have been preparation artifacts. He also confirmed this classification in *Q. alba* and *Q. velutina*. Mogensen (1975) could but speculate on how only one ovule per ovary develops into a seed. Because only ovules with a normal embryo sac have the potential to become a seed, he speculated that the first ovule in an ovary to be fertilized suppresses further development of the remaining ovules by producing a growth regulator. The capability today to culture ovules *in vitro*, while varying growth regulator and nutritional components, offers some opportunities to examine this hypothesis.

Insects also are a factor in acorn loss. Most literature deals with the impact of weevils (*Curculio* spp. and *Conotrachelus* spp.) on acorn crops (Gibson 1964, Kearby and others 1986). But weevils don't generally oviposit until midsummer after fertilization and embryogenesis has begun in the pistillate flower. Most flower loss occurs by the time embryogenesis has begun (Williamson 1966, Kossuth 1974, Cecich and others 1991), suggesting that weevils are not the major cause of poor acorn crops. For example, based on the 1990 data for *Q. alba*, about 80 percent of the flowers have aborted by mid-July (Cecich and others 1991). Assuming mid-July as the time of weevil oviposition, only 20 percent of the potential crop is present. Even if the weevils destroyed all the remaining young acorns, they would not destroy 100 percent of the potential acorn crop as has been asserted, only 20 percent. The major loss occurs before fertilization.

There is another group of insects that also deserves attention in respect to its impact on acorn crops. Treehoppers (Membracidae) are sucking insects that, depending on the species, spend most of their life cycle in the crowns of oak trees (Kopp and Yonke 1973 a,b,c, 1974). The older larval stages and young adults feed primarily on meristematic or succulent tissues and flowers. I have observed them in May and June feeding on oak pistillate flowers by inserting their stylets into the stigma of the flower. One week later these flowers were dying, dead, or abscised (Cecich and others 1991). We are presently conducting controlled feeding experiments to better define the potential impact of this insect family on flower abortion. Their possible involvement in flower loss is plausible because the insects' feeding activity coincides with the time of most of the flower abortions in early May to mid-June.

PREDICTING FLOWER CROPS

Can we predict the size or availability of a flower crop? Probably not, at least with today's information. Predicting an acorn crop may be easier than predicting a flower crop because there are visible indicators—the number of pistillate and staminate flowers and inflorescenses (Gysel 1958, Feret and others 1982). Feret and others (1982) concluded that production of *Q. alba* acorns could be best predicted from the number of peduncles borne per shoot. They found that this single variable accounted for 84 percent of the observed variability in acorn production. In contrast, I am unaware of any physiological or structural predictive indicators of flowering potential in oaks. As discussed earlier, many factors can impinge upon flower initiation and development, because of the length of time a flower primordium is exposed to potentially disruptive factors. Nevertheless, we could make the assumption that, once a flower is initiated, the pathway for its development will be continuous and successful. This "all-or-none" hypothesis can be tested by sampling a population of buds in early fall and microscopically searching for inflorescence primordia. In late winter or early spring, sample branches could be put into bottle culture indoors, forcing the buds to flush so that flowers could be observed in leaf axils. The number of inflorescences could be compared to the fall count and total number of flowers determined. Subsequently, these values would be compared to inflorescence and flower numbers from intact branches on the source tree. A significantly lower flower or inflorescence count at anthesis could indicate that either the process was disrupted or that sampling was inadequate.

An alternative hypothesis, and one that is probably more realistic, is that there are many steps to successful flower emergence in oak, beginning with inflorescence initiation. From research on annual plants, we know that there are many genes that regulate flower development (Bowman and others 1989, Shannon and Ry Meeks-Wagner 1991, Smyth and others 1990). It is not unreasonable to assume that similar genes control the development of various flower components in oak. Testing for the specific genes would require traditional breeding experiments, utilizing one or more individuals that possess a stable flower development mutation, so that the progeny could be evaluated. Unfortunately, a consequence of breeding oaks is the many years of waiting for the progeny to flower; i.e., we must wait for the juvenile-mature phase change to occur. However, current molecular technologies, such as Restriction Fragment Length Polymorphisms (RFLPs), cDNA hybridization, Random Amplified Polymorphic DNA (RAPD), are available that utilize vegetative tissues and may help to identify or locate specific flower development genes. If there were a mutation that leads to cessation of flower development, there would be no viable flower and one could not discriminate that pathway from the disrupted "all-or-none" pathway. This assumes that phase change has occurred. However, a change in gene structure (a mutation) could still be identified with these technologies.

CONCLUSION

The intent of this paper was to provide a comprehensive review of the literature and synthesize it into a plausible "story" of oak flowering biology. Easier said than done! Although there is much information about certain topics within the subject area of flowering biology, the information voids are even larger. A measure of the paucity of information about oak flower biology can be shown by restating the four questions put forth in the beginning and seeing how well they were answered.

What Should a Forester Know About Flowering?

There is still much to learn about the anatomy and physiology of oak flowers, especially the staminate flowers that produce pollen. The limited information we have from only a few species indicates that flower structure varies among species and subgenera. For *Q. alba*, the most-studied North American species, there is no complete "story" describing the continuum from initiation through seed maturation.

What Factors Affect Flowering?

Reviewing this literature was easy; there wasn't much. The long juvenile phase is important to the forest manager who wants to enhance or encourage acorn production in a young stand as soon as possible after harvesting. There is still going to be a long wait. We still don't know when initiation occurs, although the first sign of flower differentiation has been observed in two lepidobalanus species. Genetic control over the amount of flowers and seed production has been demonstrated. Emergence, receptivity, and pollen shed appear to be controlled by weather, especially temperature and relative humidity.

What Is the Relationship Between Flowers and Acorns?

Pistillate flowers don't necessarily produce acorns. In fact, most of the time they don't; which is why we're concerned about this problem. Developing acorns and leaves are apparently not competitive sinks for photoassimilates. Most flower abortion occurs before weevil oviposition; however, weevils can destroy the remainder of the crop.

Can We Predict Flower Crops?

There are no published accounts of how to predict the appearance or number of oak flowers. Because we lack so much information about flower initiation and development within the bud, it is not reasonable to estimate the time required for making reasonable predictions.

Before we can interpret how environmental, physiological, and genetic factors influence the production of flowers and acorns, we must develop a solid understanding of the flowering biology of individual species. The fragmented information for oak flowering does not lend itself to developing a clear picture of the flowering process, but it does indicate where the shortcomings exist. And, this provides guidance and opportunities for asking meaningful questions and doing the appropriate research.

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Acorns and Oak Regeneration

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ABSTRACT

Acorn production is extremely variable: among species, trees, locations, and years. From the time of flower initiation through seed maturation, a host of intrinsic and extrinsic factors, including weather, insects, disease, and flower and seed predators, combine to eliminate almost all acorns in most years. Only from bumper crops, which on the average for a given species occur once out of every 4 or 5 years, are there any acorns left over to produce seedlings. In specific locations, such complete failures may extend over periods of 10 years or longer.

Those acorns that do mature and escape predation are far from sure to produce seedlings. Viability deteriorates quickly due to drying if acorns are not covered by soil or leaf litter. The proportion of sound seed that escapes predation and chances to find conditions favorable for germination and seedling survival is very small in all but truly bumper years.

Despite the seemingly insurmountable odds, oaks have managed to keep their dominant position in the eastern hardwood forests through the buildup of advance reproduction in the form of seedlings and seedling-sprouts that result from these sporadic bumper crops of acorns. However, from a management standpoint, advance reproduction is not always in place when and where we want it, and our inability to ensure acorn production or even to predict it can severely limit our ability to regenerate a specific stand. Sporadic and unpredictable acorn crops also become major problems for planting and direct seeding due to the limited storage life of acorns.

Given our current state of knowledge, management of acorn crops is limited to ensuring that the *potential* for acorn production is in place. The most consistent finding in studies of acorn production is that only a minority of oak trees are inherently good producers of acorns. Therefore, at present, acorn crop management is largely a matter of identifying the good producers and maintaining them in a dominant position in the stand.

INTRODUCTION

There is little question that following natural disturbances and commercial harvest by a variety of means, many of the new stands will contain less oak than the previous ones. On the better quality sites the decrease in oak composition can be dramatic. The problem is generally attributed to a lack of the well-established advance reproduction that can compete with other vegetation when released. My charge in this paper is to consider: (1) How much, if any, of the oak regeneration problem is due to lack of acorns? (2) If acorns are a problem, is there anything that can be done about it from a management standpoint?

THE PROBLEM

Natural Regeneration

Very few studies have dealt directly with the relationship between acorn production and seedling establishment. In one such study Marquis and others (1976) reported that in an area with abundant advance reproduction (5,250 seedlings per acre) the number of viable seed trapped was about five times greater than in an area with poor advance reproduction (less than 100 seedlings per acre). They also found losses to rodents to be very high in the low-reproduction area and relatively low in the high-reproduction area. After depredations, almost 60 times as many seed could be expected to germinate in the area with good advance reproduction as in the low-regeneration area.

In other areas with poor reproduction the evidence pointing to lack of acorns as a factor is more speculative. Most of the information on the subject is observational and anecdotal based on the very erratic and uncertain nature of acorn production. Acorn crops are extremely variable from tree to tree, from location to location, and from year to year (Beck and Olson 1968, Beck 1977, Christisen 1955, Christisen and Korschgen 1955, Downs and McQuilken 1944, Gysel 1956, Minckler and Janes 1965, Tryon and Carvell 1962a, 1962b). In a given geographic area, acorn crops may vary year-to-year from nearly zero to over 250,000 acorns per acre. Good acorn crops may occur at long intervals—on average at intervals of 4 or 5 years. For specific stands more than 10 years may pass without good crops (Beck 1977). In the Mississippi Delta, Johnson (1979) found 100,000 Nutall oak seedlings per acre established in a good seed year. However, over the next 15 years seedlings were established in only 2 years and then in only small quantities. This variability is related to a broad array of poorly understood factors. But, sporadic acorn production—coupled with loss to predators, short storage life, seedling establishment problems, and low survival of established seedlings—no doubt contributes to scarcity of reproduction.

Artificial Regeneration

If artificial regeneration programs demand acorns and seedlings on a large scale and on a continuous, predictable basis, then sporadic seed production will become a major problem. Given the short storage life of acorns, long intervals with very low or nonexistent seed production will be highly disruptive to major planting and seeding programs.

THE PROCESS

The acorn production process—from initiation and development of flowers, through pollination, fertilization, and acorn development to germination and seedling establishment—is affected by a host of biotic and abiotic factors (figure 1). Acorns develop from fertilized flowers with all species of oak producing both male (staminate) and female (pistillate) flowers on the same tree. The white oak group (Lepidobalanus subgenus) requires 1 year for the maturation of fruit while the red oaks (Erythrobalanus subgenus) require 2 years. At each stage there are multiple factors, both intrinsic and extrinsic, which affect the process and determine whether or not mature, viable acorns will be available for regeneration. Are there critical points in the process where losses occur that are amenable to management?

The early ontogony of acorn initiation has been extensively studied and is well understood (Conrad 1900, Hartig 1851, Hjelmqvist 1953, Langdon 1939, Merkle and others 1980, Mogensen 1975, Stairs 1964, Turkel and others 1955). The most complete information for any one species on the reproductive cycle exists for whiteoak (*Q. alba* L.) (Feret and others 1982, Merkle and others 1980, Mogensen 1965, Sharp and Chisman 1961, Sharp and Sprague 1967, Stairs 1964, Turkel and others 1955). Even here there are many gaps and much disagreement as to what may or may not be the causes of the huge variability in acorn crops among trees, places, and years. And for most of the other species, the reproductive biology is very poorly understood.

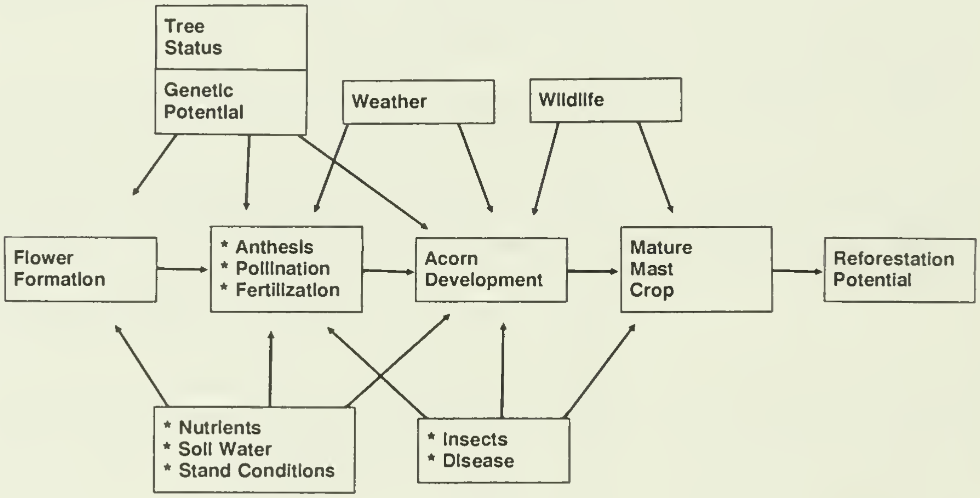

Figure 1—Acorn production—process and impacts.

Flower Formation

There is a great deal of equivocation as to whether or not flowering, or, more properly the lack of it, limits acorn production. Romashov (1957) and Sharp and Sprague (1967) stated that year-to-year acorn crop variability was not a function of variability in flower production as flowers were observed annually. Olson and Boyce (1971), in a summary of current knowledge on acorn production, concluded that flowers are formed every year in great abundance by practically every tree of flowering size, and age, and therefore, year-to-year variability in size of acorn crops is not due to lack of flowering capability, nor to cyclic formation of flowers. On the other hand, Feret and others (1982) found acorn production was significantly related to spring flower abundance for white oak in the Virginia Piedmont. Farmer (1981) and Williamson (1966) have reported great differences in flower production from year to year for white oak. The evidence is not conclusive that failure to either induce or differentiate flowers is a cause of "off" year production, but it remains a real possibility.

Anthesis, Pollination, Fertilization

Whether or not flowers are consistently developed, it is certain that the oak species frequently produce mature fruits from only a small fraction of their female flowers (Cecich 1991, 1992; Feret and others 1982; Kossuth 1974; Williamson 1966). It is not unusual for 75 to nearly 100 percent of flowers to abscise prematurely; the heaviest losses occurring early in the process prior to fertilization—the period that covers pollination and ovule development.

Numerous climatic factors have been implicated in pollen dispersal, emergence of pistillate flowers, receptivity, etc. Temperature, relative humidity, precipitation, wind, and late freezes have all been implicated at various times and localities (Goodrum and others 1971, Sharp 1958, Sharp and Chisman 1961, Sharp and Sprague 1967, Wolgast and Trout 1979). Wolgast (1972) demonstrated experimentally that high relative humidity at the time of flowering is detrimental to fruit set in scrub oak. Other conclusions about the effects of weather are based on observation and simultaneous occurrence of events, and not cause and effect relationships. Thus, the influence of weather variables on setting of fruit and subsequent acorn yield is mostly inconclusive. Cecich (1991,1992) has hypothesized that a complex of sucking insects (tree hoppers, Membracidae) may play an important role in pistillate flower abortion,. but the theory is yet to be proved.

Stephensen (1981) did an exhaustive synthesis of the literature on the proximate factors that limit fruit and seed production between anthesis and dispersal for a large number of taxonomically and ecologically diverse species that regularly abscise a large portion of their flowers and immature fruits. He concluded that, in some cases, lack of pollination, fruit and seed predation, or adverse weather may hold fruit production below the upper limit. But in most cases, resources limit fruit production. Pollinated flowers and juvenile fruits abscise until fruit and seed number match the available resources. The level of resources available for fruit development in a given reproductive episode is influenced by a host of intrinsic as well as extrinsic factors. The causes of premature abscission may well occur prior to and not in conjunction with the event.

Developing Acorns

Reasons for the premature drop of developing acorns is largely unknown. However, in a Missouri study the primary moth invader, *M. latiferreanus*, and cynipid gall wasps infested 17 percent of immature acorns collected in a 4-year study (Kearby and others 1986).

Mature Acorns

Mature acorns incur even heavier losses from insects. Weevils of the genus *Curculio* are the major culprit (Barrett 1931, Beck 1977, Beck and Olson 1968, Collins 1961, Downs and McQuilken 1944, Kearby and others 1986). However, *Conotrachelus* weevils, cynipid gall wasps, and both primary and secondary Lepidoptera have all been implicated (Kearby and others 1986). Infestation rates vary considerably from year to year, with nearly 100 percent in some years. In several long-term studies, infestation by insects averaged around 50 percent—a very significant impact (Beck 1977, Burns and others 1954, Christisen 1955, Downs and McQuilken 1944, Kearby and others 1986).

Mature acorns that escape destruction by insects face yet another hurdle. Nearly 200 species of forest wildlife consume acorns. Some, such as the large game animals, consume large quantities as individuals and in aggregate. But the sciurids (chipmunks, squirrels, etc.) probably have the largest impact (Johnson and others 1989). In looking at cumulative mast needs by forest wildlife in the Southern Appalachians, they said that acorn crops of <200 lbs/acre usually are totally consumed. And, over a period of years the demand will always exceed the supply. In a 12-year study in the Southern Appalachians at one location, production of sound acorns exceeded 200 lbs/acre only four times (Beck 1977). Average production was 186 lbs/acre and that number was influenced heavily by one bumper year with 800 lbs produced. Even in poor mast years some acorns escape predators and produce seedlings. But it takes a bumper-crop year for any appreciable number to do so.

Even those acorns which mature and escape destruction by insects and animals are far from certain to produce seedlings. Sound, undamaged acorns have a germinative capacity between 75 and 95 percent (USDA 1974). But for germination to occur, the moisture content of acorns must not drop below 30 to 50 percent for white oaks and 20 to 30 percent for red oaks (Korstian 1927). Those acorns not covered by litter or soil are very susceptible to drying. Therefore, a fairly good percentage of those acorns which mature and escape predation probably fail to produce seedlings.

POTENTIAL IMPACTS

Taking an overall view, it is evident that numerous intrinsic and extrinsic factors influence acorn production throughout the process from initiation of flowers to germination of the acorns. There is no point at which we can identify a particular factor(s) and say this factor is the cause of the problem. It is quite conceivable that a combination of factors may reduce acorn yield at a particular time or place; or at others, a single factor could be limiting, but not always the same one. Stephensen (1981) suggests, for example, that premature abscission of flowers could be due to different causes on different branches of the same tree. There is no simple or easy explanation, or fix, for the problem of sporadic, unpredictable acorn crops.

Extrinsic Factors

Various weather factors can adversely affect production. Some, such as unfavorable relative humidity at time of pollen dispersal, can limit production. Others, such as late freezes, may completely wipe out a crop at a given location. In either case there isn't much we can do about it. We do need to understand the effect of climatic factors, if for no other reason than to sort out some of the "noise" so we can better understand other factors which limit acorn production and may be more amenable to management. Understanding weather effects may also help in short-term prediction of acorn crops.

The possibility for control of the other major extrinsic factor with direct impact—insects—has been demonstrated (Dorsey and others 1962, Dorsey 1967). They were able to reduce weevil damage to white and red oak acorns using systemic insecticides. However, control of insects in a forest setting is probably not economically feasible. In seed production areas or seed orchards, experience with the pine species suggests we can control damage if there is economic demand for seed. But we need a great deal more information than we have now. Highly effective control of insect damage is unlikely, however, to eliminate poor acorn crops. But insect control does have the potential to raise the average level.

Intrinsic Factors

A great deal of attention has been focused on the extrinsic factors—mainly weather, insects, and wildlife—which directly limit acorn production. In the long run, however, whether or not acorns are produced probably depends more on intrinsic factors which determine physiological condition of the tree that allows it to initiate and develop flowers, set fruit, and supply the resources to carry the fruit to maturity.

Age/Size. One of the more obvious factors is tree age and/or size. There are records of acorn production from very young trees of sprout origin (Wood 1934) and from a few short-lived species such as scrub oak (Wolgast 1972, Smith 1929, Little and others 1958). However, most species do not begin production until the trees are around 20 to 25 years old (USDA 1974, Reid and Goodrum 1957). They also suggested that crowded trees appear to begin production later than trees with more growing space. Some workers suggest that substantial yields of acorns cannot be expected earlier than age 40 (Goodrum and others 1971). Yields apparently increase with age and or at least with size up to a point, level off for an extended period, and then decrease (Downs and McQuilken 1944). But the yield-age relationship is anything but clear.

Crown Position. Crown size and dominance has been shown to be a major determinant of acorn production (Carvell and Korstian 1955, Christisen and Korschgen 1955, Matthews 1963, Reid and Goodrum 1957). Drake (1991) found that only 9 percent of suppressed trees and 38 percent of intermediates produced seed, and those that did, produced only small quantities. Although there was much variation among trees in terms of quantity, 75 percent of codominants and 96 percent of dominants produced at least some seed.

Inherent Capability. The most consistent finding in acorn production studies across all species and under the most diverse environmental conditions is that some trees are consistently good producers and others consistently poor producers, and the differences are not related to obvious characteristics of the trees (Burns and others 1954, Christisen 1955, Christisen and Korschgen 1955, Collins 1961, Cypert 1951, Cypert and Webster 1948, Downs 1949, Downs and McQuilken 1944, Feret and others 1982, Goodrum and others 1971, Reid and Goodrum 1957, Sharp 1958, Smith 1929, Tryon and Carvell 1962, Wood 1934). These production tendencies are most often attributed to inherent capabilities. Wolgast (1972, 1977) lends support to this thesis with his studies of scrub oak. Good, medium, and poor producers were transplanted to a common site but retained their production tendencies. Farmer (1981) found strong clonal control over acorn yield in a grafted white oak seed orchard. In a good seed year clonal differences accounted for over 50 of the variance in percentage of shoots flowering, number of flowers and inflorescences per shoot, percentage of flowers maturing to acorns, and acorn yield.

MANAGEMENT IMPLICATIONS

Of the major extrinsic factors (weather, insects, and wildlife) which limit acorns available for regeneration, none is very amenable to management in the general forest setting. Weather variables have the potential to reduce or completely eliminate an acorn crop in a given time and place. And we need a better grasp of the impacts of weather variables if we expect to understand the overall process. But we are not likely to exert any direct control in the near future under any circumstances.

Insects are potentially very damaging to the acorn crop at many stages of the production process. Numerous insects feed on foliage of oaks. Their impact on acorn production has not been assessed. But such insects as aphids have been shown to have large impacts on nut production in species such as pecans by depleting available energy. It has been hypothesized that premature abscission of flowers may be related to leaf hoppers. It has been observed repeatedly that weevils destroy 50 percent of mature acorns on an average. Experience with seed orchards and seed production areas for the southern pines demonstrates the possibilities for control of insects when an economic demand exists. However, the technical base does not exist for the oak species even if the demand were there.

It is technically possible to reduce animal depredations by reducing or excluding animal populations. But in a forest setting it is probably not ecologically desirable or politically possible to reduce populations. In fact mast production specifically for wildlife may often be a management objective. It is probably possible to reduce animal depredations in seed orchards; but even there, reducing losses to wildlife will not be a major way to increase acorns available for regeneration.

At the present time the best chance for acorn production enhancement is in applying what we know about tree-to-tree variation. We should recognize and manage those trees capable of producing large acorn crops on a consistent basis. The large inherent differences among trees in productive capability have been observed and reported numerous times over the past 50 years. But this knowledge has not been applied due to the difficulty in identifying acorn producers. Given the many other factors that may impact production in a given year, identification of consistent producers is not always easy to do. Maintaining the good acorn producers in the stand in a dominant position is currently the only practical way to enhance acorn production.

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Insects and Diseases Affecting Oak Regeneration Success

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ABSTRACT

Flowers, acorns, seedlings, sprouts, and mature oaks are damaged and killed by myriad insects and diseases, but relatively few have been shown to prevent successful oak regeneration. The best known are acorn-infesting insects (*Curculio* weevils, the filbertworm, and gall wasps) and root diseases of nursery-grown seedlings caused by *Phytophthora* spp. and *Cylindrocladium* spp. Preventing insect infestation of mature acorns is not yet possible but hot water treatments are used to kill weevil larvae already inside acorns. Management of nursery root diseases is accomplished through the integration of sanitation, soil management practices, and soil fumigation. Emerging pest management issues in oak regeneration include flower pest identification and assessment, control technologies for seed production areas, alternatives to methyl bromide-chloropicrin soil fumigants in nurseries, and the effects of oak decline on natural regeneration opportunities in upland oak forests.

The wide distribution and diversity of oaks in the U.S. are matched by the vast array of diseases and insects affecting them. However, relatively few pests have been conclusively shown to significantly affect the ability to regenerate oak. These are acorn-infesting insects and nursery root diseases. This paper focuses on the most damaging pests in these two groups and presents proven options for controlling them. Other pest management issues are discussed that may emerge with increased emphasis on artificial regeneration and with large-scale ecological impacts resulting from the interactions of oak decline and insect defoliation in the Southeast.

ACORN-INFESTING INSECTS

Acorn-infesting insects are the most studied group of pests affecting oak regeneration. There are several types of insects involved but the most notorious among them are several *Curculio* weevil species. Virtually all oak species are attacked by one or more of 22 different weevils recorded by Williams (1989).

Adult weevils are themselves not damaging. However, larvae hatching from eggs laid in late summer in tiny niches beneath the shell may consume most of the nut tissue within a few weeks. When larvae mature, they bore out through the shell and migrate underground to pupate. The rate of infestation is variable but has exceeded 90 percent in some northern red oak collections (Gibson 1982). Single acorns are commonly hosts to three or more larvae; embryos in infested acorns that escape damage may germinate but seedlings grow slower than those from uninfested acorns (Oliver and Chapin 1984).

Infestation rates of the filbertworm (*Melissopus latiferreanus*) are much lower than for acorn weevils (Gibson 1982), but they have been responsible for large losses, particularly in low production years (Drooz 1985). Damage is caused by larval feeding and is usually lethal to infested acorns. Adult moths lay single eggs on leaf surfaces near acorn clusters in mid-summer. After hatching, the larva crawls to an acorn, bores through the shell, and begins feeding. The mature larva exits the acorn after 3 to 5 weeks, spins a cocoon in the top few inches of soil, and pupates in winter.

Non-stinging gall wasps are another group of primary acorn pests. Like *Curculio* spp. and the filbertworm, they infest and can kill intact acorns. There are many species that form unusual galls on various oak tissues, but *Callyrhytis operator* and *C. fructuosa* are the most common in acorns. Gibson (1982) found them to be less ubiquitous than either weevils or filbertworms in northern red oak acorn collections. However, the infestation rate of *C. fructuosa* was second only to weevils in two collections made in consecutive years from a Tennessee seed orchard (L. Barber and author, unpublished data[1]). Acorns infested by *C. fructuosa* appear normal on the outside but are filled with up to 2 dozen larvae encased in small stony galls. *C. operator*, on the other hand, forms a gall in the side of the acorn shell. Gall wasps have complicated life cycles, and the same species may induce galls on different plant parts at different times of the year.

Some insects and pathogenic fungi and bacteria can invade acorns damaged by other agents and thereby increase losses. The best known insects with this mode of action are *Conotrachelus* weevils and the acorn moth, *Valentinia glandulella*. Neither can breech intact acorns, but the acorn moth has been known to attack otherwise healthy, germinating acorns (Galford 1986). Examples of pathogens following acorn damage are a bacterium, *Erwinia quercina*, and a fungus, *Fusarium solani*. *E. quercina* causes a disease in California live oak (*Q. agrifolia*), called drippy nut, after it gains access to acorns through oviposition punctures of gall wasps (Hildebrand and Schroth 1967). The name of the disease describes the main symptom, which is the byproduct of anaerobic fermentation and results in acorn rot and premature abscission. *F. solani* was isolated from weeviled acorns collected in Mississippi (Vozzo 1983) and Tennessee (author, unpublished data[2]). The fungus can cause damping-off and root disease in seedlings, but it's impact in these cases is unknown since saprophytic forms exist and pathogenicity was not confirmed experimentally.

Control of Acorn-Infesting Insects

Hot water treatment is the best proven method for controlling weevil larvae in infested acorns. The key elements are water temperature and duration of treatment, but critical thresholds apparently vary with tree species. Crocker and Morgan (1983) prescribed 30-45 minutes at 43 °C followed by quenching in cold water for live oak acorns without causing undue loss of viability. At the Fusiform Rust Resistance Screening Center in Asheville, N.C., northern red oak acorns are treated for 40 minutes at 49 °C ±1 °C and air dried. Floating acorns are discarded and the rest stored in plastic bags after dusting with fungicide (Knighten and others 1988).

[1,2] Data on file, Southern Region, Forest Pest Management, Asheville, N.C.

Germination after this treatment has been estimated between 80 and 90 percent after 6 months cold storage and 20 percent after 4.5 years (J. Knighten, personal communication). Other acorn-infesting insects are presumed to be killed along with weevil larvae. Research is needed to identify the critical parameters for acorns of different species and to determine if and when heat treatment is necessary. Bonner and Vozzo (1987) and Crocker and Morgan (1983) have suggested that, for some seedlots, the benefits of heat treatment in weevil larvae control might be outweighed by detrimental effects on germination and early growth.

Treatments for preventing infestation do not exist. Some systemic insecticide treatments reduced weeviling and increased the percentage of sound acorns in northern red oak and white oak (Dorsey and others 1962, Dorsey 1967) without depressing germination (Tryon and others 1968). However, all of the tested chemicals have high mammalian toxicity (LD_{50} less than 15 mg/kg). One of the successful chemicals (Bidrin®= dicrotophos formulated as a water soluble injectable) is EPA-registered for use on oak.

NURSERY ROOT DISEASES

Tree seedlings grown in large numbers in confined areas under the lush growing conditions typical of nurseries are subject to damage from a whole suite of pests not normally found in forested settings. Defoliating insects, foliage disease, shoot cankers, and root diseases can cause dramatic symptoms in nurseries. However, the most widespread and damaging of oak nursery pests are root diseases caused by fungi in the genera *Phytophthora* and *Cylindrocladium*. They have tough resting spore stages that can survive very harsh conditions and persist in soil for long periods in the absence of suitable hosts. *P. cinnamomi* is a virulent pathogen of many oak species in nurseries, most notably northern red oak (Crandell and others 1945). It is a member of a group of fungi known as water molds that are favored by periodically wet soil conditions and have a swimming spore stage that attacks feeder roots. Once established in the root system, the fungus spreads to larger laterals and the tap root. *Cylindrocladium* spp. have no mobile spore stage but they form densely compacted masses of fungal tissue in soil and colonized plant parts called sclerotia that resist all but the most aggressive of control measures. Several different *Cylindrocladium* spp. have caused root rot in cherrybark (Smyly and others 1977) and shumard oaks (Affeltranger and Burns 1983) in bareroot nurseries and in northern red oak grown in containers (Oak and Triplett 1985).

Root-diseased seedlings may display a range of above-ground symptoms including pre- and post-emergence damping-off, stunting, top dieback, foliage yellowing, and premature defoliation. Below ground, infected root systems are sparse, stunted, and usually blackened. Obviously diseased seedlings are easily recognized and culled, but those with less distinct symptoms may be outplanted and die later or grow slower than healthy seedlings.

Control of Nursery Root Diseases

Nursery root disease losses have been most effectively avoided where sanitation, soil management, and chemical measures have been combined into an integrated pest management system (Cordell and others 1989). Sanitation starts with excluding the pathogens that can be transported to uninfested areas in contaminated soil by thoroughly cleaning equipment that has been used in infested areas. If pathogens become established, then a vigilant inspection schedule, culling of affected stock, and in extreme cases, quarantine, can reduce losses. Soil management practices that have an important influence on root disease probability include crop rotation, choice of cover crops, managing water, and in containerized nurseries, choice of growing medium. Continuous seedling cropping leads to increased populations of pathogens, and some cover crops are also hosts for seedling pathogens. For instance, legume crops increase inoculum levels of *Cylindrocladium* spp., but grass cover crops do not (Soloman and others 1987). Inadequate drainage or over-watering can simultaneously increase inoculum of *Phytophthora* spp. and increase seedling susceptibility by depressing seedling vigor and inhibiting normal root development. Commercially prepared "artificial" growing media are preferred in container systems over mixtures that include field soil, due to the risk of introducing pathogens and the difficulty in eradicating them once introduced (Oak and Triplett 1985).

Root pathogens are among the most difficult nursery pests to control chemically. Several soil fumigants are EPA-registered but the most effective are formulations containing 67 percent methyl bromide and 33 percent chloropicrin (Cordell and others 1989). Proper soil preparation, soil moisture, temperature, and deep placement of the fumigant are essential for effective treatment. Fungicide drenches applied to the soil (e.g. metalaxyl for *Phytophthora* spp. and benomyl for *Cylindrocladium* spp.) are registered for nursery sites and are widely prescribed, but the research basis for recommending them to control root diseases in oak seedlings is lacking.

OTHER PESTS

Other diseases and insects can cause dramatic damage with consequences for oak regeneration success but they are usually limited in time or geographic distribution. Spring oviposition of cicadas (*Magicicada* spp.) results in dieback of shoots that bear flowers and developing acorns. There are many species with life cycles ranging from 4 to 17 years, but damage is most dramatic when overlapping broods of periodical cicadas emerge simultaneously (Borrer and others 1976). Root feeding by nymphs reduced growth but not acorn yield of bear oak in New York (Karban 1985).

The success of natural oak regeneration is usually determined not by pests, but by the competitiveness of seedlings, seedling sprouts, and stump sprouts relative to the propagules of other species that might displace it. However, cankers on stump sprouts caused by *Botryodiplodia gallae* have resulted in repeated regeneration failures in mixed oak stands on poor sites after clearcutting in a National Forest in Michigan (Croghan and Robbins 1986). Cankers caused by *Botryodiplodia* spp., as well as other relatively weak pathogens, are common on twigs and branches of stressed trees in both forested and ornamental settings, but rarely have they been seen as the primary cause of death of trees. Except for avoiding the use of clearcutting, management guidelines do not yet exist. Silvicultural treatments to encourage regeneration from seedlings or seedling sprouts are being explored.

EMERGING PEST MANAGEMENT ISSUES

It seems likely that the use of direct seeding and planting will increase as means for compensating for oak reproduction shortages in many settings. Presently, seed requirements are met by wild collections, but small seed orchards are reaching seed-bearing age. The value of the crop in these special areas is high enough that costly pest management strategies unthinkable in forest settings become feasible. While prevention of acorn weevil infestation is the most urgent pest control priority given current knowledge, there is a large gap in knowledge concerning the role of other pests in seed production. Therefore, the highest pest management priority in seed production areas is pest identification and assessment. Efforts in this area have already begun as a component of research into oak flowering and acorn production biology. Monitoring in Missouri and Tennessee has revealed that mature acorns can represent as little as 3 or 4 percent of the initial flower crop (L. Barber, R. Cecich, unpublished data).[3] Treehoppers (Homoptera: Membracidae) have been found killing oak flowers in Missouri during the period when losses are most pronounced (R. Cecich and others 1991), but the relative importance of insects, weather, and other potentially limiting factors is unknown.

Once pests are identified, control technologies will be needed. Parallels in pine seed orchard pest management include new pesticide formulations; new application techniques for existing pesticides; behavioral chemicals for insect population monitoring, insecticide application timing, or mating disruption; and orchard cultural practices. A filbertworm sex pheromone has already been identified and is used in commercial filbert nut orchards for population monitoring and for timing insecticide treatments (Aliniazee 1983).

Soil fumigation is the only management response available when nursery root diseases are found. EPA review of the most effective methyl bromide-chloropicrin formulations underscores the need for alternatives in the event that label registrations are withdrawn. Research is needed in soil population monitoring, the delineation of inoculum levels associated with damage under different nursery conditions, and alternative control measures including biocontrol.

Most references to oak regeneration problems are for high-quality sites, but oak decline has the potential to limit natural regeneration opportunities in mature oak stands growing on drier sites. There is no doubt that large areas are being affected by oak decline. Over 1 million acres of oak forest type were affected in the northern Piedmont and Appalachian Mountains of Virginia in 1986 (Oak and others 1991). Preliminary estimates for the Piedmont and mountains of North Carolina were about .9 million acres in 1990 (R. Sheffield, unpublished data).[4] The regeneration impacts are less clear, however. Acorn production potential is reduced as a result of crown dieback and tree mortality (Oak and others 1989). Advanced physiological age, root disease, and carbohydrate physiology prevent vigorous sprouting of overstory trees in decline areas. Whether these effects result in an inability to adequately regenerate oak depends on the abundance and competitiveness of oak propagules relative to other species that might displace it. Monitoring of a declining scarlet oak/black oak stand in Missouri over 5 years showed overstory mortality increasing from 36 to 62 percent and shifts in understory composition towards white and post oaks, red maple, and shortleaf pine

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[3] Data on file, Southern Region, Forest Pest Management, Asheville, N.C., and North Central Forest Experiment Station, Columbia Mo.

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[4] Data on file, Southeastern Forest Experiment Station, Asheville, NC.

(Johnson and Law 1989). Oaks will probably be a smaller component in the next stand and oak species diversity will be less. Similar conclusions were reached after 8 years of monitoring in gypsy moth defoliated areas of the Pocono Mountains in Pennsylvania (Gansner and others 1983), where the greatest oak losses were in areas suffering repeated, heavy defoliations. Pre-defoliation decline conditions were not reported. On the George Washington National Forest in Virginia, the combined effects of pre-existing oak decline and gypsy moth defoliation have resulted in 22,500 acres of severe mortality accumulated between 1987-1991. Research is needed into the interactions of oak decline, insect defoliation, overstory competition, understory composition, and regeneration timing as well as options for dealing with stands suffering severe mortality from decline and defoliation.

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Sources of Oak Reproduction

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ABSTRACT

There are three juvenile growth forms of oak that silviculturists commonly term "reproduction": (1) *seedlings,* (2) *seedling sprouts,* and (3) *stump sprouts.* A seedling is a form that has not experienced shoot dieback. Seedlings become seedling sprouts by surviving shoot dieback and resprouting one or more times. Seedling sprouts may persist and accumulate for decades in xeric forests and sometimes in mesic and hydric forests that are recurrently burned, grazed, or otherwise disturbed. Stump sprouts arise from the stumps of cut overstory trees after a thinning or final harvest and sometimes from the bases of fire-killed trees. When present before a silvicultural event such as clearcutting or shelterwood removal, all three growth forms are collectively called *advance reproduction.* The number, size, and spatial distribution of oak advance reproduction and the capacity of the parent stand (overstory) to produce oak stump sprouts can be used to assess a stand's oak *regeneration potential,* i.e., its capacity to occupy and dominate growing space at a specified time in the new stand. Because the population dynamics of oak reproduction vary greatly among species and different kinds of oak forests, this variation should be recognized in assessing stand regeneration potential.

REGENERATION TACTICS AND STRATEGIES OF OAKS

Oak forests can regenerate from seed and vegetatively from sprouts. *Seeding,* various modes of *sprouting,* and vegetative multiplication represent different *tactics* that oaks use in their *regeneration strategy.* Although all of the North American oak species rely to some extent on both seeding and sprouting, they differ greatly in their dependence on one tactic versus the other. For a given species, regeneration strategy may vary among regions and disturbance regimes. The large number of oak species that occur in the Eastern United States and the wide range of sites they occupy suggest that regeneration strategies are likely to vary greatly among the oaks.

Associated with these regeneration tactics are three commonly recognized growth forms that are collectively termed oak "reproduction"[1]: (1) *seedlings,* (2) *seedling sprouts,* and (3) *stump sprouts.* Seedlings originate directly from seed

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[1] *Reproduction* herein refers to seedlings and juvenile sprouts of tree species. *Reproduce* refers to the creation of new individual plants, either from seed or by certain vegetative processes of plant multipliction (e.g., the spreading and subsequent separation of individual plants in lignotuberous oak species of the arid Southwest). *Regeneration* refers to the ecological *process* of renewing and sustaining populations of reproduction. These definitions may differ from those adopted by others (cf. Harper 1977).

and have not experienced shoot dieback. The seedling state typically lasts only one or a few years, depending on environment. Seedlings become seedling sprouts after dying back and resprouting one or more times. They may persist for decades, depending on species and environment. Stump sprouts arise from the stumps of cut overstory trees and sometimes from the bases of trees whose tops have been killed by fire or other injuries. When present before a silvicultural event such as clearcutting or shelterwood removal, all three growth forms are collectively termed *advance reproduction*. All living oaks from seedlings to mature trees thus can contribute to the *regeneration potential* of a stand. Regeneration potential is the capacity of a species to occupy and dominate growing space at a specified time in the new stand.

In the relatively droughty oak forests of the Missouri Ozarks, which are often dominated by some combination of black oak (*Q. velutina* Lam.), white oak (*Q. alba* L.), scarlet oak (*Q. coccinea* Muenchh.), and post oak (*Q. stellata* Wang.), the total density of oak advance reproduction typically ranges from 1,000 to 2,000 seedlings and seedling sprouts per acre. After a good acorn crop, 150 to 300 new oak seedlings per acre may become established (Sander 1979). But success in regenerating these forests largely depends on the relatively few oak seedling sprouts (e.g., about 400 per acre) with large root systems capable of supporting rapid shoot growth after overstory removal (Sander and others 1984). The regeneration of oaks in the Missouri Ozarks is thus largely dependent on sprouting, and with few exceptions these forests are seldom successionally displaced by other species.

Oaks of the arid Southwest may regenerate almost exclusively by sprouting. For example, Gambel oak (*Q. gambelii* Nutt.) produces three distinct root-like structures: lignotubers, rhizomes, and true roots (Tiedemann and others 1987). Lignotubers are burl-like structures with adventitious buds, which are the primary source of new shoots when tree crowns are killed. Several lignotubers may be connected by rhizomes, which have fewer buds. Rhizomes facilitate the development of wide-spreading clones (Muller 1951) that quickly develop from the seedling state (Christensen 1955). Later, the physical separation of individual lignotubers resulting from the death of connected lignotubers within a clone results in a form of plant multiplication that is important to the species' regeneration. Gambel oak thus regenerates primarily by sprouting from lignotubers and rhizomes, whereas seedlings are usually only a minor source of reproduction (Harper and others 1985). Muller (1951) concluded that rhizomes in oaks are associated with arid and semiarid climates where environments are especially unfavorable for germination and seedling survival. In addition to Gambel oak, other rhizomatous oaks in the United States include live oak (*Q. virginiana* Mill.) and several shrubby oaks native to the arid Southwest.

Northern red oak (*Q. rubra* L.), which occupies the middle ground between wet and dry extremes throughout its wide range in the eastern deciduous forest, is relatively flexible in its regeneration strategy. This flexibility is evidenced by large numbers of new red oak seedlings after bumper acorn crops (Johnson 1974), potentially rapid seedling shoot growth (Farmer 1975), ability to regenerate from seedlings established after final harvest (Johnson and others 1989), and capacity to sprout from large parent trees of advanced age (P. S. Johnson 1975, Wendel 1975). But unlike the xeric oak forests of the Missouri Ozarks and elsewhere, northern red oak forests are frequently displaced successionally by other species (Crow 1988, Johnson 1976, Loftis 1990a, Lorimer 1989, Nowacki and others 1990).

Although sprouting is an important attribute of all oaks, there is growing evidence that seeding may be an important regeneration tactic of some bottomland oaks. For example, recent studies have shown that water oak (*Q. nigra* L.) seedlings established after final harvest can be important contributors to the stocking of the new stand (Golden and Loewenstein 1991, Loewenstein 1992). But bottomland oaks also can sprout prolifically, which favors their development in stands disturbed by fire, grazing, and other factors (Aust and others 1985). These oaks, neither *obligate* seeders or sprouters, are flexible in their regeneration strategy. The relative importance of seeding as a regeneration tactic is also sometimes revealed by the number of seedlings that occur after a bumper acorn crop. For example, Nuttall oak (*Q. nuttallii* Palmer) seedlings exceeded 100,000 per acre in a southern bottomland forest after a bumper acorn crop (R. L. Johnson 1975). If only 0.1 percent of those seedlings (100 per acre) were competitively successful and well distributed, they would capture much of the available growing space within 20 years of overstory removal. The inherently rapid growth of Nuttall oak reproduction (Johnson 1981) and the productive sites they grow on may further reinforce this species' seeding strategy.

In bottomland oak forests, competing non-oak reproduction such as green ash (*Fraxinus pennsylvanica* Marsh.) and sweetgum (*Liquidambar styraciflua* L.) nevertheless often outgrow and suppress oak reproduction after overstory removal (Johnson and Krinard 1983, Aust and others 1985). Moreover, periods of high oak advance reproduction density in hydric forests are often followed by prolonged periods of low seedling density because of low seedling survival rates and infrequent acorn crops (R. L. Johnson 1975). There are thus frequent and prolonged periods with little or no oak advance reproduction. Consequently, bottomland oak forests are often successionally displaced by other species.

These anomalies in regeneration strategy among the oaks emphasize the difficulty of generalizing the regeneration problem across oak species and regions. Different oaks have different ways of solving their regeneration problems, and some species are more flexible than others (figure 1). In turn, flexibility in regeneration strategy is shaped by each species' environment and genetics.

SEEDLINGS AND SEEDLING SPROUTS

The unpredictable nature of flowering in oaks results in the irregular occurrence of acorn crops and thus new seedlings (Cecich 1991). On the average, most species produce a good acorn crop once every 3 or 4 years (Olson 1974). Numerous biotic and abiotic factors influence acorn viability, germination, initial seedling establishment, and survival. For example, dry weather, droughty soils, and freezing temperatures can reduce acorn viability and germination (Korstian 1927). Acorn crops also are frequently destroyed by unpredictable but frequent infestations of acorn weevils (Christisen and Kearby 1984). Most of the remaining acorns may be consumed by rodents, deer, birds, and other animals (Marquis and others 1976, Sork and others 1983). So, even after a bumper acorn crop, few acorns may be available for seedling production. Among the few remaining viable acorns, many fall into microsites unsuitable for germination and seedling establishment. Significant numbers of new oak seedlings thus occur as unpredictable population waves associated with bumper acorn crops and a patchy spatial distribution. The relatively infrequent occurrence of large seedling populations originating from one acorn crop (cohort) usually coincides with a bumper acorn crop combined with other fortuitous events, such as weather, that favor the preservation of acorn viability through fall and spring germination periods and low populations of acorn consumers.

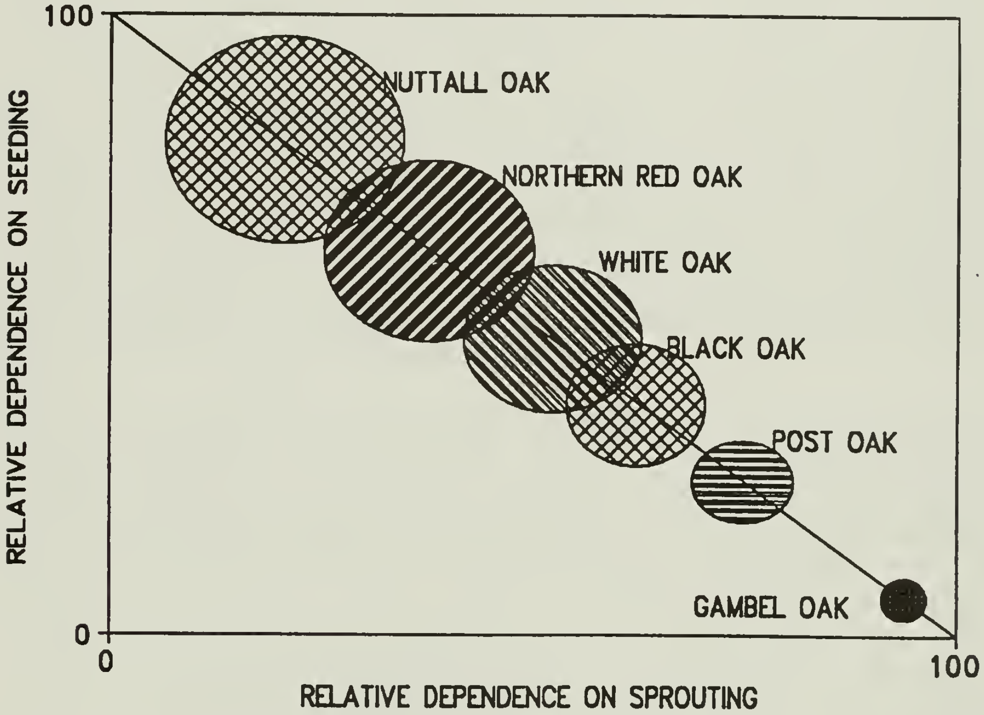

Figure 1—Conceptualized dependence on seeding versus sprouting as a regeneration tactic for six oak species. [Diameters of circles are proportionate to species' flexibility in selecting the alternative tactic.]

Several studies have shown that survival of northern red oak seedlings originating from a single cohort is influenced by overstory density and other stand characteristics (figure 2). In general, reducing overstory density increases seedling survival and growth (Beck 1970; Crow 1992; Loftis 1988, 1990a). A dense layer of lower story trees, shrubs, or ground cover also can reduce seedling survival and growth (Beck 1970, Loftis 1990a, Scholz 1955). Other factors that can reduce oak seedling survival include animal browsing, insect defoliation, droughty soils, inadequate light, and frost (Crow 1992, Gottschalk 1988, Hanson and others 1987, Korstian 1927, McGee 1988).

During their first 9 years, numbers of northern red oak seedlings from a single cohort in North Carolina declined exponentially beneath the parent stand (figure 2A). Unfortunately, there are few detailed reports of oak seedling survival of similar duration. Short-term studies nevertheless point out the great variation in survival rate among seedlings of the same species growing in various regions representing different stand densities and different light and competition environments. They also establish the range over which we might reasonably expect the survival rates of oak advance reproduction to recur. For example, after

5 years, survival of individual cohorts of northern red oak seedlings ranged from about 0.16 to 0.86, depending on overstory density or understory competition (figure 2).

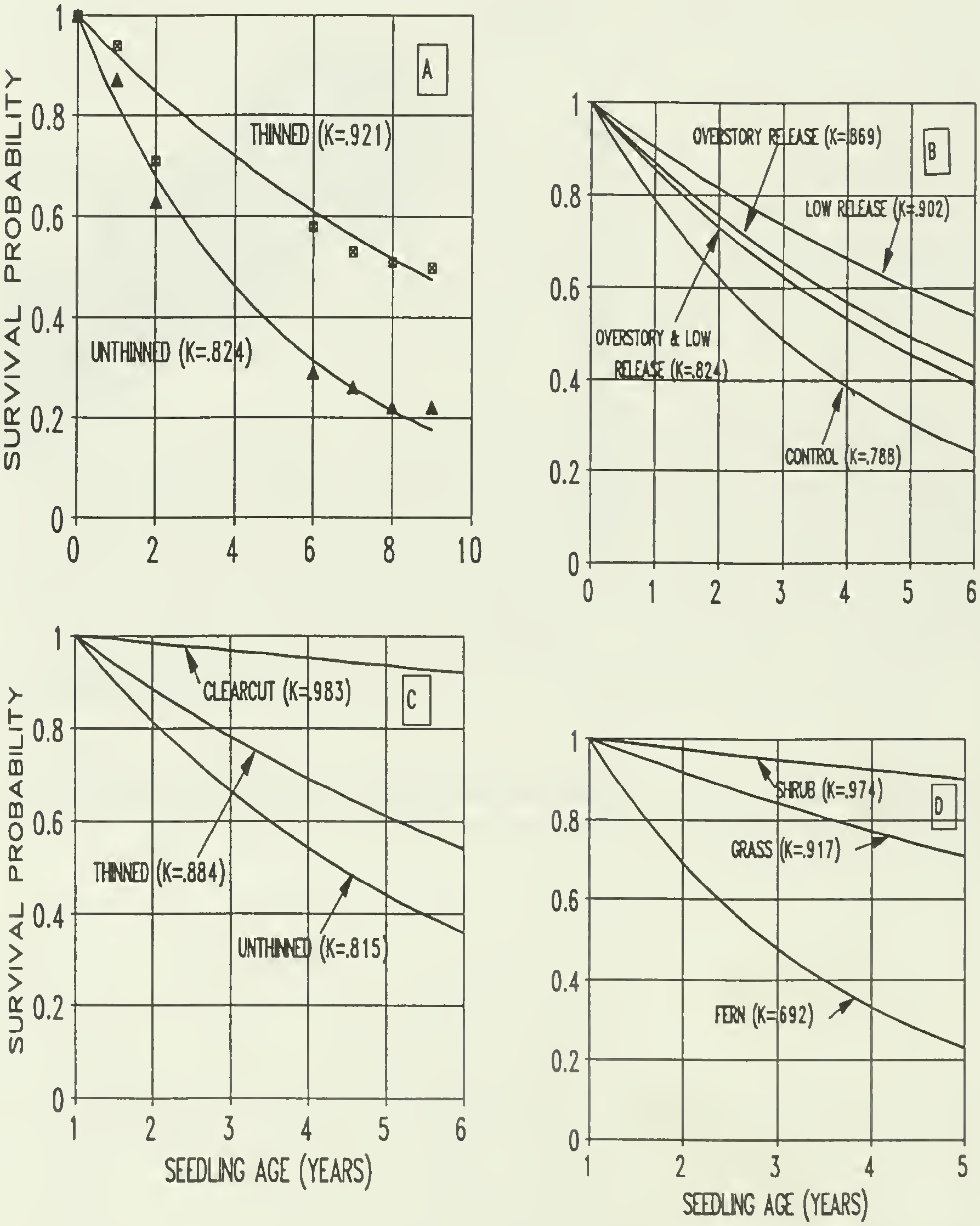

Figure 2—Survival curves for northern red oak seedlings originating from single acorn crops (cohorts) expressed as a negative exponential annual survival rate (*K*) from age 0 (germination) or age 1 year. [Survival probability $(P) = K^y$, where y = years since initial population census, i.e., years since $P = 1$. (A) Under thinned and unthinned mesic forests in North Carolina (adapted from Loftis 1988); (B) In four overstory/understory release treatments in mesic forests in North Carolina (adapted from Beck 1970); (C) In clearcut, thinned, and unthinned stands treated with an herbicide in dry-mesic forests in northeastern Wisconsin (adapted from Crow 1992); and (D) Competing with three classes of ground cover under fully stocked mesic forests in southwestern Wisconsin (adapted from Scholz 1955)].

But the acorn producing capacity of a stand, and thus the rate of seedling input into oak forests, changes with time. Large trees usually produce more acorns than smaller trees because, other factors being equal, acorn production increases with crown area. In turn, crown area is correlated with bole diameter (Goodrum and others 1971). However, in some species there is a threshold diameter above and below which acorn production decreases (Downs 1944). Large, senescent oaks are poor acorn producers (Huntley 1983). The production of acorns per unit of crown area is also greater in open-grown trees than in forest-grown trees of the same size (Gysel 1956, Sharp 1958). Moreover, some trees are better acorn producers than others even when tree size and environmental factors are the same (Sharp and Sprague 1967). For example, in mature white oaks in Pennsylvania, only 30 percent produced any acorns even in good seed years (Sharp 1958), and an even smaller percent produced a good crop in those years (Sharp and Sprague 1967). So, although variation in stand structure and age can account for some of the variation in both the temporal and spatial variation in oak seedling establishment, inherent variation in acorn production among trees introduces an essentially random element into predicting seed and seedling inputs into oak forests.

Despite the seemingly complex problem of predicting the establishment of oak seedlings, more than half the variation in the density of black oak and white oak advance reproduction in xeric forests in northern Lower Michigan was explained by relatively simple measures of overstory density and structure (Johnson 1992). For both species, 55 percent of the variation in reproduction density was explained by total overstory basal area and the basal area of "large" trees presumed to be the primary seed producers. Large trees were defined as those at least 14 in. d.b.h. for black oak and those at least 12 in. d.b.h. for white oak (figure 3). The related models also showed that, per unit basal area of large trees, white oak was more efficient at producing seedlings than black oak. Moreover, high densities of black oak reproduction were favored under low density stands, whereas the reverse was true for white oak. Other studies have shown that topographic factors, stand history, and site quality also influence oak reproduction density (Arend and Scholz 1969, Carvell and Tryon 1961, Nowacki and others 1990, Ross and others 1986, Walters 1990).

Because the seedling stage is usually brief, seedling sprouts are the predominant form of oak reproduction in many, if not most, oak forests. Seedlings can sprout from dormant buds anywhere along the stem between the root collar and the terminal bud cluster. Dieback and resprouting seem to be important processes in the life of oak reproduction. Although recurrent shoot dieback is common to most hardwoods, it is especially prominent and ecologically important in the xerophytic oaks, which are morphologically and physiologically adapted to survival in environments subjected to repeated fire and drought (Abrams 1990, Grimm 1984, Wuenscher and Kozlowski 1971).

The natural environment of seedling sprouts of the xerophytic oaks imposes stresses that periodically decrease shoot mass and leaf area through shoot dieback. Surviving seedling sprouts thus develop increasingly greater root:shoot ratios as roots grow incrementally larger and shoots recurrently die back. In turn, high root:shoot ratio and large root mass enable oak reproduction to opportunistically respond to favorable environmental conditions by facilitating two or more long flushes of shoot growth (multiple flushing) during one growing season (Dickson 1991, Johnson 1979). Conditions that are usually favorable for the growth of oak

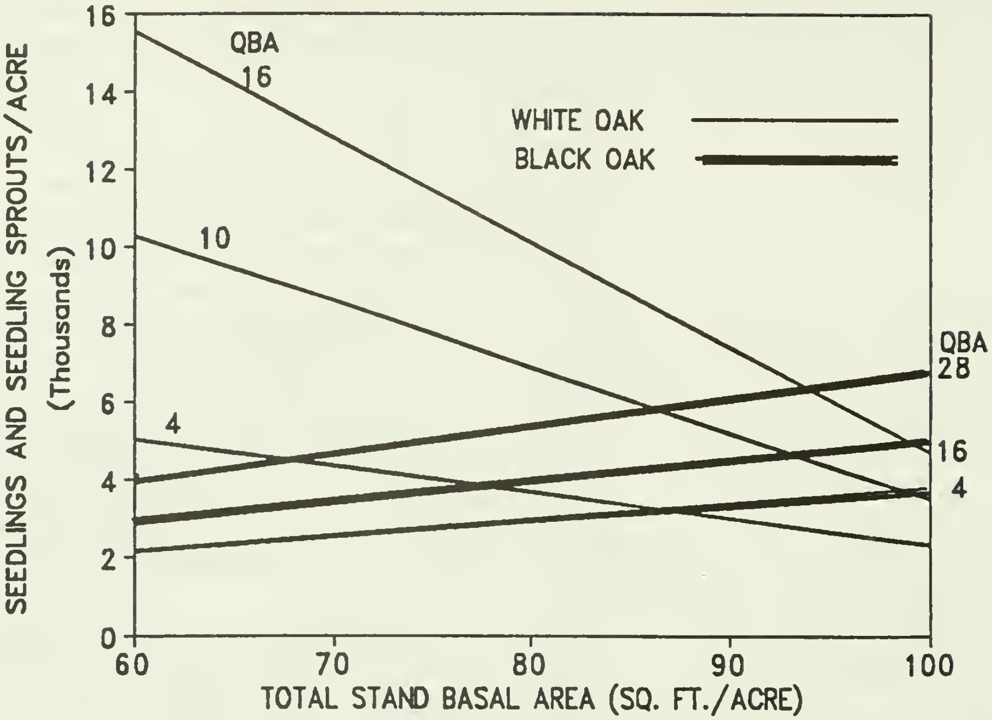

Figure 3—Estimated density of black oak and white oak advance reproduction in relation to total stand basal area and the basal area of "large" trees of the same species (*Q*BA) in xeric oak forests in northern Lower Michigan. [The trees comprising *Q*BA are the presumed primary acorn producers. For white oak, *Q*BA includes trees ≥12 in. d.b.h., and for black oak, trees ≥14 in. d.b.h. The models explain 55 percent of the variation in reproduction density of both species (from Johnson 1992).]

reproduction are created by timber harvesting and forces that destroy the overstory including fire, windthrow, insects, and disease.[2] Successional replacement of oak by oaks thus heavily depends on conditions that favor the long-term accumulation of oak reproduction with high root:shoot ratios and large root mass. Lacking those characteristics, oaks are usually at a competitive disadvantage. This is especially true of the reproduction of the xeromorphic upland species, which grow slowly even under optimal conditions until they develop the requisite root mass and root:shoot ratio. Shoot dieback thus may be an important aspect of the evolutionary development and adaptive strategy of oaks.

The accumulation of oak reproduction under a parent stand is one of the most important aspects of the regeneration ecology of oaks. Oak silviculturists call this "advance reproduction" because, in the even-aged management of oaks, it is present in advance of final harvest. Its presence and development largely determine the importance of oaks after natural or human-caused events that destroy or remove the parent stand. Oaks opportunistically capitalize on this accumulation process because it facilitates the capture of growing space when the overstory is destroyed or removed. This capacity largely depends on the characteristics of the competing vegetation and the accumulated population of oak seedling sprouts with large roots.

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[2] An exception occurs when the removal of the protective overstory canopy precedes a spring frost that kills the new spring shoot growth of oak reproduction (Johnson 1979, McGee 1988).

The size distribution and age distribution of this population, in turn, depend on the balance of birth, death, and growth rates of reproduction intrinsic to each type of oak forest.

Nevertheless, it is the number, size, and spatial distribution of all three classes of reproduction that largely express the total oak regeneration potential of a stand (Sander and others 1984). With the possible exception of some bottomland oak forests, sustaining oak dominated forests largely depends on perpetuating preestablished reproduction (propagules) from one generation to the next. Whether the overstory is removed in small gaps or over large areas, the resulting spatial units of reproduction are even aged. Although oaks generally are not recognized as species well adapted to capturing small canopy gaps (Crow 1988, Ehrenfeld 1980), they have the potential to do so if advance reproduction of sufficient size is present. For example, 10-ft.-tall advance reproduction of northern red oak captured canopy gaps as small as 1/25-acre in a mixed sugar maple-oak stand in southwestern Wisconsin (Lorimer 1983).

Recurrent fire promotes the accumulation of oak reproduction in at least three ways: (1) By eliminating or reducing the number of fire-sensitive understory competitors, including shrubs and shade-tolerant trees, (2) By reducing overstory density by killing trees with thin, fire-sensitive bark, and (3) By killing the tops of oak reproduction, which increases the root:shoot ratio of those that survive by resprouting. The first two factors increase light on the forest floor, which in turn creates conditions more conducive to the accumulation of oak reproduction. Although poorly adapted to surviving under shade, oak reproduction is well adapted to surviving fire because of the concentration of dormant buds near the root collar. These buds often remain an inch or more below the soil surface where they are protected from lethally high temperatures (Korstian 1927).

Many xeric oak forests appear to be relatively stable and show little evidence of succession to more shade tolerant or mesophytic species. Probably the largest North American forest of this type occurs in the Ozark Plateau in Missouri. However, even in that region, the successful development of advance oak reproduction varies with topographic features such as slope position and aspect, which collectively control light, heat, and soil moisture (Sander and others 1984). Such forests occur on the drier sites throughout the central and eastern region including the Ohio Valley (Minckler and Woerheide 1965), the Appalachians (Ross and others 1986), and the Lake States (Johnson 1966).

Oak reproduction often may be absent or scarce on mesic or hydric sites in the absence of disturbance (Carvell and Tryon 1961, R. L. Johnson 1975, Will-Wolf 1991). Nevertheless, oak reproduction densities in these forests may at times exceed 50,000 seedlings per acre in mesic forests (Tryon and Carvell 1958) and 100,000 per acre in bottomland forests (R. L. Johnson 1975). When oak seedlings do occur, they may represent only one or two acorn crops. Because of low survival rates, most of the seedlings from a single cohort may die before the next good acorn crop occurs. The rapid rate of seedling disappearance results largely from the shade-intolerance of oak reproduction and the low light levels on the forest floor (Hanson and others 1987). In the absence of disturbance, these forests typically possess high overstory basal areas and multiple subcanopy layers (Braun 1967, Loftis 1990b). Such vertical stratification occurs in mesic and hydric oak forests throughout the deciduous forest region.

Microsites where oak advance reproduction becomes initially established in large numbers may not be where it ultimately survives to form populations with large root systems (Harrison and Werner 1984, Johnson 1966). Although initial establishment is favored by cool moist sites such as those on northeast-facing slopes, long-term survival is favored by the more southerly and neutral southeast and northwest aspects where overstory density and vertical stratification of crowns tend to be lower than on the more mesic northeast aspects (Sander and others 1984, Walters 1990, Carvell and Tryon 1961).

There is a general relation between site quality and regeneration success: the better the site the more difficult it is to regenerate oaks (Arend and Scholz 1969, Loftis 1990b, Lorimer 1989, Trimble 1973). Obtaining the accumulation of oak reproduction necessary for successful regeneration on highly productive sites requires recurrent disturbance. Historically, fire was associated with the origin of oak stands (Abrams 1992, McGee 1979). Thus, one way to sustain oak-dominated forests on productive sites may be prescribed burning. Based on a review of research on prescribed burning in eastern hardwoods and southern mixed pine-hardwood stands, Van Lear and Waldrop (1988) concluded that fire, if correctly used, can be effective in regenerating oaks. However, fire also can kill or damage oaks and thus reduce the economic value of stands (Loomis 1973, Rouse 1986).

STUMP SPROUTS AND RELATED GROWTH FORMS

Stump sprouts originate from dormant buds at or near the base of the stump of a harvested overstory tree. In the silviculture of central hardwoods, overstory trees are defined as those 2 in. d.b.h. and larger (Roach and Gingrich 1968). However, that definition has not been universally adopted. The biological distinction between a stump sprout and a seedling sprout is nevertheless arbitrary because all oaks, from small seedlings to large standing trees, have some potential to produce basal sprouts when the parent stem is cut. When wind, fire, or other factors destroy an oak stand, sprouts also may develop from the bases of trees that have broken off or from standing trees with dead tops.

For several species of oaks, the percentage of stumps expected to produce sprouts after timber harvesting can be estimated from tree diameter and tree age (Johnson 1977). In general, the frequency of sprouting decreases with increasing tree diameter, age, and site quality (figure 4). But other factors, such as season of cutting and shading, also can affect stump sprouting in hardwoods. For some species of oaks, there is evidence that stumps sprout more frequently when trees are cut or killed during the dormant season than during the growing season (Clark and Liming 1953, Kays and others 1988). However, some of the live oaks of the Western United States sprout prolifically regardless of season of cutting (Longhurst 1956). Although sugar maple stumps exposed to full light sprouted more frequently than shaded stumps (Church 1960), similar responses of oak stumps to shading have not been reported. McGee and Bivens (1984) observed that numbers of stems in white oak sprout clumps were about the same for stumps that had been released from directly overtopping trees and stumps that were not released. Regardless of treatment, nearly 100 percent of the stumps of trees between 2 and 8 in. d.b.h. sprouted. Larger trees or those older than 60 years produced few or no sprouts.

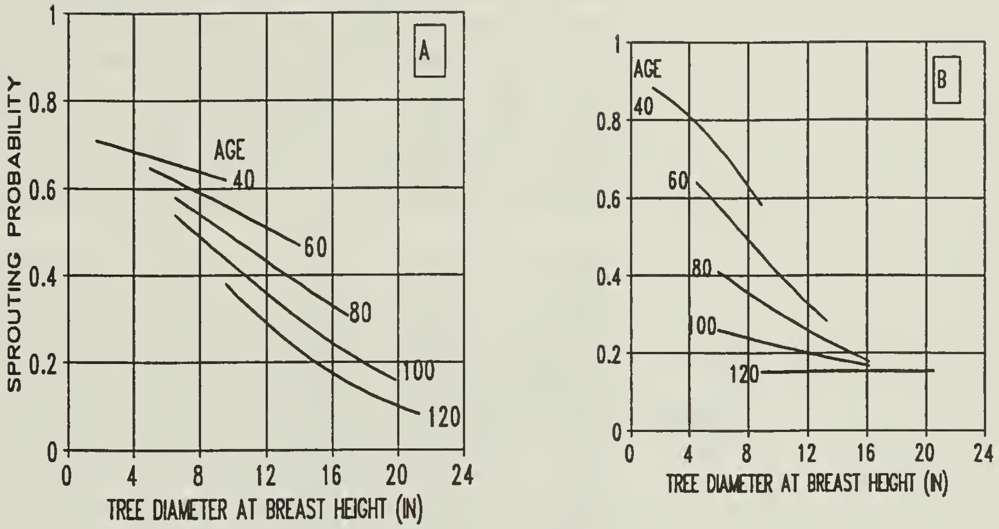

Figure 4—Estimated sprouting probabilities for (A) black oak stumps and (B) white oak stumps in the Missouri Ozarks in relation to parent tree diameter and age (years) when site index is 65 ft. (base age 50) (from Johnson 1977).

Stump sprouts originating from pole-size and larger parent trees are, in effect, mature root systems connected to juvenile shoots. This root:shoot combination results in rapid height growth. During their first decade, open-grown stump sprouts can produce four or more flushes of shoot growth per year totaling 3 ft. or more even under droughty conditions (Cobb and others 1985, Johnson 1979, Reich and others 1980). The large root mass of stump sprouts and their large carbohydrate storage and absorptive capacity, together with other factors, facilitate multiple flushing in oaks. In contrast, multiple flushes are not produced in mature oaks, shaded seedlings and seedling sprouts, and small seedlings and seedling sprouts under water stress (Borchert 1976, Buech 1976, Cook 1941, Johnston 1941, Kienholz 1941, Longman and Coutts 1974).

Frequency of flushing and total shoot elongation in oaks usually decline as stems increase in size and age and as root systems approach their maximum size. The number of flushes in scarlet oak stump sprouts decreased from an average of about two per growing season the first year to one by the fourth growing season (Cobb and others 1985). Thus, by the fifth year, the pattern of shoot growth approached that of the single flush of a mature tree. The progression from multiple to single flushes may be attributable to a declining root:shoot ratio that results in increasingly longer periods for roots and shoot to restore "functional balance" after shoot elongation and leaf expansion (Borchert 1975).

The number and spatial distribution of sprouts around the stump also influence sprout growth. The importance of sprout distribution around the stump may be related to the pattern of vascular connections that develop between sprouts and the parent tree root system, with each stem helping to sustain a portion of the root system (Kharitonovich 1937, Kramer and Kozlowski 1979, Roth and Sleeth 1939, Wilson 1968).

In the Missouri Ozarks, the number of sprouts per stump was positively correlated with the early height growth of five oak species (Johnson 1977). The same relation also was observed for various oak species in other regions (P. S. Johnson 1975, Ross and others 1986, Schwarz 1907). Collectively, the observed spatial distribution and clump density effects suggest that numerous well-distributed sprouts maintain the parent tree root system and thus an efficient root-shoot feedback system that promotes rapid early height growth.

However, the apparent benefits of a balanced distribution of stems and high clump density are short lived. In Wisconsin, rapid growth of the dominant stem in unthinned clumps of 4- to 23-year-old northern red oak stump sprouts was associated with high clump density (P. S. Johnson 1975). Similarly, northern red oak clumps thinned to one stem as early as age 4 subsequently grew faster than stems in unthinned clumps (Johnson and Rogers 1984). This would seem to indicate that competition between stems in the same clump begins very early. However, 12-year-old northern red oak stump sprouts in Appalachian forests did not respond to clump thinning (Lamson 1988). Although northern red oak commonly initiates several dozen sprouts, stem crowding soon induces rapid stem mortality so that by the end of the first decade only four or fewer stems per clump typically remain. But this natural clump thinning process varies greatly among and within species (*cf.* P. S. Johnson 1975, Roth and Hepting 1969, Schwarz 1907).

The diameter of the parent tree and the correlated size of the root system also affect the growth of oak stump sprouts. For five species of oaks in the Missouri Ozarks, the correlation between stump diameter and height growth of the dominant stem within a sprout clump was consistently negative for 5-year-old sprouts of all species (Johnson 1977). However, the opposite was true of oak sprouts in Virginia (Ross and others 1986). Such discrepancies might be explained by the range of stump diameters observed in any given study. For example, data from a study of black oak and white oak sprouting that included trees ranging from less than 1 in. to more than 12 in. in basal diameter showed that the most rapid height growth occurred in clumps originating from 6-in. stumps (Johnson 1979). Sprouts from stumps larger or smaller than that grew less. The height growth of oak reproduction thus changes continuously, but not unidirectionally, from small advance reproduction to large-diameter overstory trees (figure 5).

Because of the large variation in number of stems per clump within a stump diameter class, we might expect roots and shoots of many young sprout clumps to be physiologically imbalanced. Accordingly, among the imbalanced clumps, rapid changes in clump structure would be expected as the clumps move toward functional balance. This view is supported by the initially large but rapidly decreasing variation in shoot growth among dominant shoots within black oak and white oak sprout clumps during the first 4 years (Johnson 1979). The large amount of unexplained variation in the relation between shoot growth and stump diameter also reflects rapidly changing root-shoot relations. Other factors that may be significant sources of variation in the shoot growth of oak sprouts include site quality, genetic variation, competition, parent tree age, and season of cutting. The significance of these factors may vary among oak species and regions.

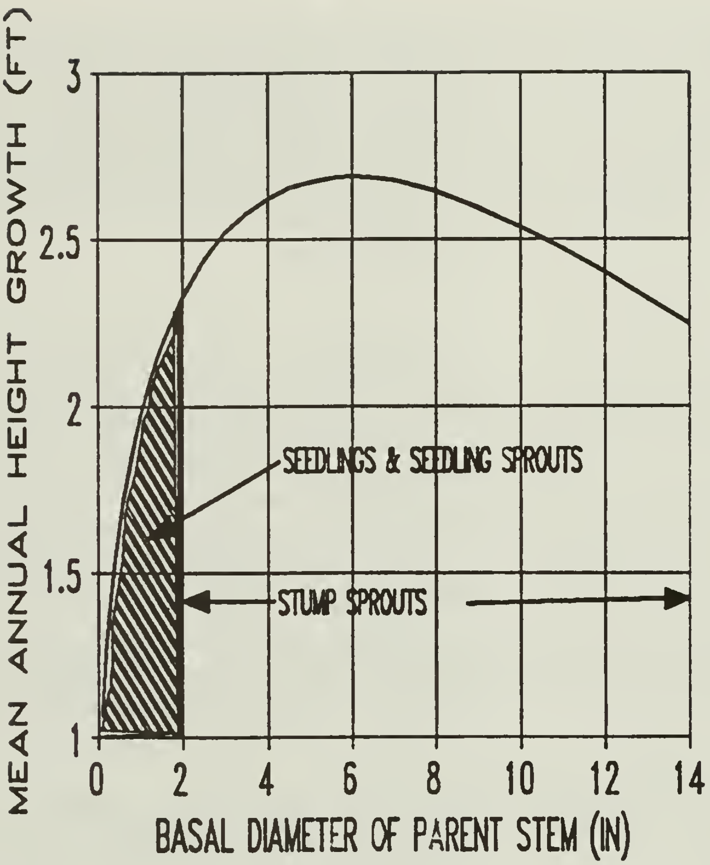

Figure 5—Relation between height growth of black oak and white oak reproduction and parent stem basal diameter during the first 4 years after clearcutting in the Missouri Ozarks (adapted from Johnson 1979).

ASSESSING REGENERATION POTENTIAL

Oak stands can be regenerated by completely removing the overstory on small to large areas using clearcutting, shelterwood, or group selection methods (Hannah 1987, Sander and Clark 1971) and possibly by using other methods that substantially reduce overstory density. Those regeneration methods are used because oak seedlings and sprouts cannot grow into the overstory as long as they are heavily shaded. But all the oak seedlings and sprouts present at the time of a regeneration cut do not contribute to the future stand. A clear picture of the future stand is thus hidden, or encoded, in certain characteristics of the present stand. The most important of these characteristics are the number, size, and spatial distribution of the oak advance reproduction; the composition and structure of the overstory; and site quality (Loftis 1990a, Sander and others 1984).

If the parent oak stand is to be replaced by another generation of oaks, enough oak reproduction of sufficient size must be present at the time of final harvest (Carvell and Tryon 1961, Sander and Clark 1971, Trimble 1973). But even when the essential characteristics of the oak reproduction are known, it is difficult to assess the contribution of oaks to the regenerated stand because of the unpredictable growth of reproduction. Much of this uncertainty is related to the difficulty of obtaining an accurate measure of root size. Growth of oak reproduction largely depends on root size, which may be much larger and older than the above-ground stem. Recurrent stem dieback and resprouting of oak reproduction beneath an overstory may go on for decades before the reproduction expresses its growth potential. This potential is finally expressed when the overstory is harvested or when it is destroyed by natural events such as fire, windthrow, and disease. Although some silviculturists can predict general regeneration trends after timber harvesting based on experience and observation, more quantitative methods are needed to accurately assess the *probable* contribution of oak reproduction to future stand stocking.

Unfortunately, root size is impossible to measure in practical application. The next best measure of the growth potential of reproduction is probably its diameter just above the ground. However, the relation between shoot growth and basal stem diameter, although usually statistically significant, is relatively weak (Dey 1991, Johnson 1979, Sander 1971). To overcome this problem, some predictive regeneration models employ probabilistic methods to assess the importance of oaks in the future stand (Dey 1991, Loftis 1990a, Sander and others 1984). Other regeneration models use other methods (Waldrop and others 1986, Marquis and others 1984). Regardless of their derivation, regeneration models are useful silvicultural tools for assessing stand regeneration potential. Using such models usually requires an inventory of the advance reproduction and the overstory. The practical application of predictive regeneration models thus does not differ greatly from the application of growth and yield models.

Because site quality and competition vary greatly among different kinds of oak forests, ecological classification is a silvicultural tool that can aid in assessing stand regeneration potential. The objective of ecological classification is to define landscape units (ecosystems) *within* which there is great ecological similarity and *among* which there is dissimilarity (Rowe and Sheard 1981). In principle, all stands representing a given unit respond similarly to natural forces and processes and thus to management practices. This does not mean that stands of similar overstory composition and structure are necessarily ecologically equivalent units. In ecological classification, factors such as climate, physiography, parent materials, soils, and lesser vegetation, together with the composition and structure of the overstory, are used to define ecological units. This feature distinguishes ecological classification from traditional forest cover-type descriptions (e.g., Eyre 1980). Defined units thus can be used to distinguish among oak-dominated ecosystems that are superficially similar but ecologically quite different.

Both predictive regeneration models and experience-based assessments of regeneration potential can be developed in conjunction with ecological classification. In either case, increased accuracy of predictions should result because similarities in site, competition, and other factors are intrinsic to each defined ecological unit. For example, from our general understanding of oak regeneration processes, we would expect the rate of accumulation and size distribution of oak reproduction to vary substantially among different kinds of oak forests. Ecological forest site classification and its development and application have been discussed elsewhere (Barnes and others 1982, Cleland and others 1985, Kotar 1991, Rowe 1981). There are classification systems for several areas of the eastern hardwood region (e.g., Albert and others 1986, Hix 1988, Host and Pregitzer 1991, Kotar and others 1988, McNab 1987, Miller 1981, Smalley 1986).

Whether assessments of regeneration potential are based on quantitative models or on experience and general observation, the regeneration potential of all sources of oak reproduction should be considered. But the relative importance of the various sources of reproduction and their population dynamics can be expected to vary among oak species and across the landscapes where they occur. An understanding of the biology and population dynamics of all sources of oak reproduction is therefore prerequisite to a practical understanding of the regeneration ecology of oaks and thus the silvicultural methods required to sustain oak forests.

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Prediciting & Modeling Oak Regeneration

Predicting Oak Regeneration—State of the Art

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ABSTRACT

Early efforts to predict species composition of regeneration (including oaks) resulting from harvest cuts attempted to link presumed species successional status and/or shade tolerance rating to the level of disturbance or residual stand stocking. While this traditional view of forest succession seems applicable in some situations, there are so many exceptions that its applicability as a model for prediction is questionable. Implicit in more recent efforts to predict oak regeneration following harvest cuts is a contemporary set of succession concepts that deal with population dynamics, initial floristic composition, vital species attributes, or life history characteristics. These models recognize that oaks are generally regarded as advance-growth-dependent species and predict the expected oak component in regeneration as a function of the amount and size distribution of advance growth—stump sprout potential and advance reproduction—in an existing mature stand.

INTRODUCTION

In this brief introduction to the next two papers, I would like to focus on a few forest succession concepts that are relevant to regeneration in general, and to prediction in particular. If, for a particular stand, one has a goal of regenerating a new oak stand or maintaining an oak component in the new stand, having the ability to predict the consequences of a range of regeneration alternatives is critical in choosing an appropriate silvicultural treatment.

RELAY FLORISTICS VS. INITIAL FLORISTIC COMPOSITION

The first two concepts are posed as alternative views of vegetation development (Egler 1954). Relay floristics (figure 1) presents a very familiar pattern of development, one that many people would associate with Clements (1916). Well-defined seral stages, beginning with pioneer species, successively occupy a site, culminating in a relatively stable community of climax species. We also usually tend to think of pioneer species as shade intolerant and of climax species as shade tolerant.

In using this concept to predict the outcome of the application of various regeneration methods, we have associated species we classify as pioneer and shade intolerant with clearcutting, climax and shade tolerant species with selection methods, and species that are intermediate in their successional status and shade tolerance with shelterwood. And one frequently hears that "cutting sets succession back to an earlier stage."

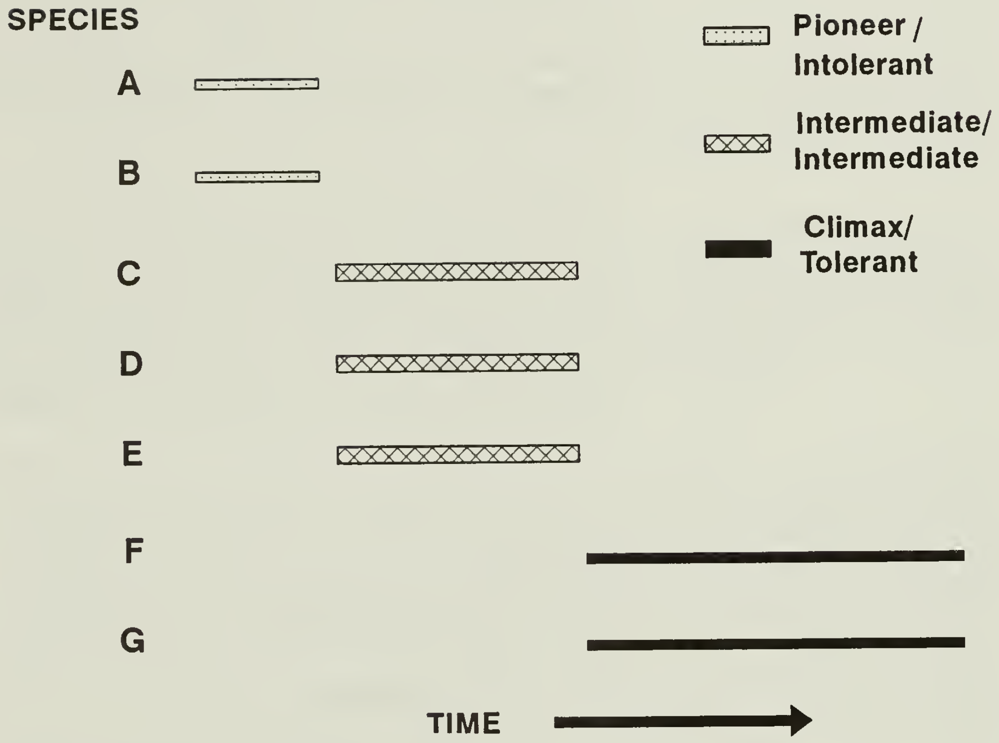

Figure 1—Relay floristics model.

However, reconciling this neat scheme with observed outcomes of regeneration methods is problematic, particularly in hardwood forests. For example, clearcutting a stand of oaks on a relatively xeric site frequently results in a new stand dominated by oaks, but oaks are not usually considered pioneer species. Regeneration cuts of any kind in some hardwood forests result in excellent representation of species we regard as climax and shade tolerant in the new stand. Further, the application of different regeneration methods in some forest types frequently results in the same species composition. In short, categorization of species by presumed successional status lends little to our ability to predict species composition resulting from regeneration cutting.

As an alternative to relay floristics, Egler proposed a concept he called initial floristic composition (figure 2). This concept suggests that species composition of vegetation following disturbance is determined by the propagules that exist on the site at the time of the disturbance and those which arrive early in the process of stand development. Changing species dominance over time results from differential growth and development of species present. Interestingly, it was Clements (1916) who first made this observation. According to Clements, logging does not initiate a successional sequence because propagules of a variety of species are left after logging. Rather, it creates a dysclimax.

For forest trees, then, species composition following disturbance is determined by the initial load of propagules—stump- and root-sprouts and advance reproduction of the various species that occur in the stand, and by new seedlings that become established soon after the disturbance from buried seed or from seed blown or carried into the stand. The essential feature of the initial floristic composition concept that makes it useful for prediction modeling is that the individuals of species that form the dominant tree canopy 50 to 100 years after disturbance come from the initial load of propagules. A corollary to this concept is that variations in species composition among stands 50 to 100 years after similar disturbances results from variations among stands in the initial loads of propagules.

A number of investigators have recognized the general applicability of the initial floristic composition concept to hardwood stand development following disturbance (e.g. Oliver 1981, Leopold and others 1985, Shugart 1984, Drury and Nisbet 1973). From the standpoint of developing prediction models, we can model the post-disturbance development of existing advance growth—both advance reproduction and stump or root-sprout potential—and we can deal in probabilistic sense with input and development of new seedlings.

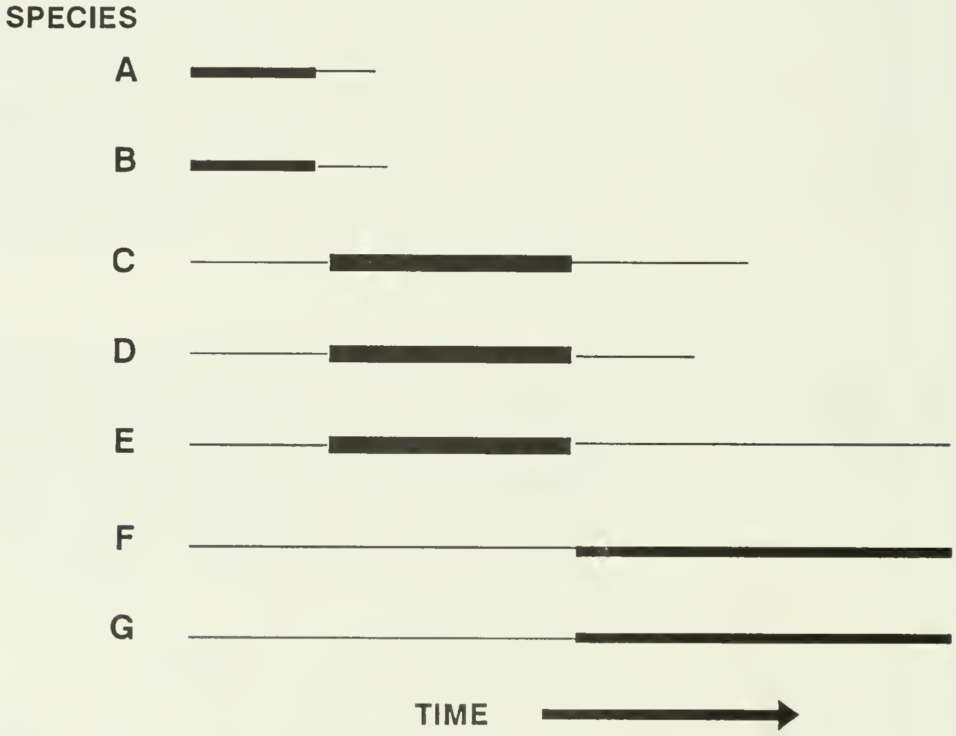

Figure 2—Initial floristics model.

VITAL ATTRIBUTES OF SPECIES

Noble and Slatyer (1980) suggested that species composition of stands that develop after disturbance could be predicted from three vital attributes of species:

1. The method of arrival or persistence of a species at a site during or after a disturbance.
2. The ability to grow to maturity in the developing stand.
3. The time needed for an individual of a species to reach critical life stages.

Because of time constraints, I will discuss only the the first two of these vital attributes.

Several authors have addressed the first attribute by examining the primary reproduction source that is characteristic for various species (Beck 1988, Kelty 1988, Johnson 1989). Oaks, for example, are considered to be highly dependent on advance growth; i.e., they persist through a disturbance as advance reproduction and stump sprouts. Yellow-poplar is an example of a species that usually becomes established after disturbance as new seedlings from seed stored in the forest floor.

The second attribute, the ability to grow to maturity in the developing stand, has been, and is being, addressed more fully for oaks than for any group of hardwood species of which I am aware. In general, the fairly strong relationship between preharvest size of advance growth and its post-harvest development are being used to predict the amount of oak one would expect in the next stand.

FINAL NOTE

Initial floristic composition, vital attributes of species, and concepts from population biology are the ecological bases for the oak regeneration potential concept (P. Johnson, this Proceedings) that provides the framework for developing models to predict how much oak we might expect in a new stand following a regeneration cut. Some models already exist, but prediction models are lacking for many ecosystems where oaks are important and for regeneration methods other than clearcutting. But the development and application of these prediction models will help us choose among alternatives. For managers the application of these prediction models has one very clear imperative: a commitment to collect adequate data about existing stand conditions.

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Predicting Quantity and Quality of Reproduction in the Uplands

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ABSTRACT

The structure of regeneration models is determined by the sources of reproduction and by the biotic and abiotic factors that affect population dynamics of the ecosystem being modeled. Sources of reproduction include new seedlings, advance reproduction, and sprouts from the cut stumps of overstory trees. The micro-environment (e.g., light, temperature, and soil moisture) influences the development of reproduction. Aspect, slope position, elevation, and site index are commonly used to express the integrated effect of micro-environment on reproduction. In some upland oak ecosystems, wildlife may adversely affect stand regeneration potential. Interference species such as ferns, fire cherry, red maple, and flowering dogwood may dominate the site following harvest, thereby reducing the regeneration potential. The importance of these factors in influencing regeneration potential varies among regions. Thus, regeneration models must be developed for specific regions. ACORn is an example of a regional stand-level regeneration model developed for even-aged forests in the Missouri Ozarks. It can be used to predict future stand characteristics by species and diameter classes, which in turn, can be used as input for growth and yield simulators.

INTRODUCTION

Growth and yield models can simulate the development of even-age stands that are about 20 years of age and older. In the Central States, growth models such as TWIGS (Miner and others 1988), STEMS (Belcher and others 1982) and OAKSIM (Hilt, 1985) can be used to project stand changes resulting from real or hypothetical management practices. However, none of these models can predict stand structure or composition of the new stand. During the first two decades after final harvest, rapidly changing tree growth and competition relations determine the character of the mature stand.

The oak reproduction that develops after clearcutting depends on the oak regeneration potential of the parent stand. Regeneration potential refers to the capacity of a species or species-group to occupy and dominate growing space at a specified time in the new stand. For oaks, it can be determined from preharvest characteristics of the parent stand, including the advance reproduction and the overstory. To quantify the regeneration potential of a stand, the various sources of reproduction thus must be considered.

Natural reproduction after final harvest may come from new seedlings, advance reproduction, and sprouts from stumps of overstory trees (Beck 1980). New oak seedlings usually grow slowly and are not a major source of reproduction in most ecosystems (Sander and Clark 1971, Sander 1972, McQuilkin 1975). Viable acorns remain in the forest floor for 6 months or less because they are rapidly consumed by wildlife, damaged by insects and pathogens, and dessicate or freeze during the winter.

Advance reproduction and stump sprouts usually are the major sources of reproduction. The competitiveness of upland oak reproduction usually depends on the development before final harvest of a large root:shoot ratio. Oak advance reproduction can develop large root:shoot ratios through repeated shoot dieback and resprouting. Shoot dieback may result from water stress, weather damage (i.e., frost and freeze), insects, pathogens, fire, and browsing. Nevertheless, oak reproduction may accumulate and develop in the understory for decades (Merz and Boyce 1956, Tryon and others 1980). Once the overstory is removed, larger stems of advance reproduction can sprout vigorously and thus capture much of the newly available growing space (Carvell 1967; Sander 1971, 1972, 1979; McQuilkin 1975; Beck and Hooper 1986; Ross and others 1986; Johnson and Sander 1988; Loftis 1988). Thus, it is the number, size, and spatial distribution of oak advance reproduction that largely determines the oak regeneration potential of a stand.

Sprouts from cut stumps of overstory trees are usually the fastest growing form of oak reproduction (Spaeth 1928, Kuenzel 1935, Sander and Clark 1971, Smith 1979, Zahner and Myers 1984). The large food reserves and absorptive capacity of the parent root system support rapid shoot growth of stump sprouts. Stump sprouts make up variable portions of the total oak reproduction and often compensate for deficiencies in oak advance reproduction (Johnson and Sander 1988).

REGENERATION MODELS

There are several hardwood regeneration models for predicting stand development after final harvest. Predictions are based on preharvest inventories of advance reproduction, the overstory (trees larger than 1.6 in. d.b.h.), and site factors. These models thus provide land managers the opportunity to evaluate alternative prescriptions before actual harvest. Methods for evaluating the natural regeneration potential of upland oak forests have been developed by Sander and others (1976, 1984), Johnson (1977), Johnson and Sander (1988), Lowell and others (1987), Waldrop and others (1986), Loftis (1988, 1990) and Marquis and Ernst (1988). Models for evaluating the potential contribution of planted trees to future stocking also have been developed for northern red oak (*Quercus rubra* L.) (Johnson 1988) and other hardwoods (Johnson 1984, Johnson and Rogers 1985).

Marquis and Ernst (1988) developed an expert system for Allegheny hardwood forests called SILVAH. Its application produces prescriptions based on management objectives, present stand conditions, and projections of tree growth and regeneration potential (Marquis and others 1992). To evaluate even-aged stands, critical stocking values are used to predict regeneration success. In applying the system, advance reproduction is inventoried on plots 6 ft. in radius. Whether a plot is stocked depends on species, numbers of stems, and their size. For example, a plot is considered stocked with oak if there are at least 25 stems less than 4.5 ft. tall, or if there is one stem greater than 4.5 ft. tall. Oaks in the overstory also are inventoried. The number of reproduction plots expected to be stocked with oak stump sprouts at stand age 20 are estimated using models developed by Sander and others (1984). During the preharvest inventory, limiting site factors (poor drainage and stone content), amount of interference species competition, and intensity of deer browsing also are noted. Because these factors reduce the regeneration potential of a stand, the number of plots deemed stocked with desirable reproduction are accordingly reduced. The number of plots stocked with desirable tree species thus determine whether or not the regeneration potential is adequate. In general, when 70 percent of the plots are stocked with desirable advance reproduction, successful regeneration is expected to occur.

Loftis (1990) developed a regeneration model for mixed hardwood forests of Southern Appalachia. The model projects eighth-year post-harvest heights and crown classes of northern red oak advance reproduction based on preharvest measurements of advance reproduction and site quality. Heights of red oak reproduction 8 years after final overstory removal are estimated from preharvest height and basal diameter of advance reproduction and from site index. Preharvest basal diameters and site index are then used to predict the probability that a given stem of oak advance reproduction grows to dominant or codominant crown classes in the new stand at age 8. This model thus can be used to evaluate the contribution of red oak reproduction to the future stand.

Sander and others (1984) developed a regeneration model for the Missouri Ozarks. It predicts the probability of individual oaks surviving and attaining a specific future height that places them in codominant or dominant crown classes. From preharvest inventories of the overstory and advance reproduction, the model predicts the adequacy of future oak stocking. A stand is deemed to have adequate regeneration potential if projected stocking of dominant and codominant oaks at stand age 20 is at C-level or greater based on Gingrich's (1967) stocking relations. However, the model is unable to predict the diameter distribution of oaks in the new stand, and non-oaks are not considered. Although species such as blackgum (*Nyssa sylvatica* Marsh.), sassafras (*Sassafras albidum* (Nutt.) Nees, hickory (*Carya* spp.), and flowering dogwood (*Cornus florida* L.) seldom occur as dominant trees in Ozark forests once they reach 20 years of age, they do affect the development of stands during the first two decades after final harvest because of their high density and rapid growth. These species are also important to wildlife and biodiversity.

In contrast to some other deciduous forests of the Eastern United States, the forests of the Missouri Ozarks regenerate primarily from sprouts of harvested overstory trees and advance reproduction. Therefore, the composition and size structure of the future stand is largely determined by the species composition and size structure of the preharvest advance reproduction and overstory. By observing these features together with measurements of site factors such as slope, aspect, and site index, model users can predict the composition and structure of the new stand.

A COMPREHENSIVE OZARK REGENERATOR

Dey (1991) developed a regeneration model called A Comprehensive Ozark Regenerator (ACORn) to simulate the regeneration of even-aged stands in the Missouri Ozarks. It was developed from measurements of individual stems of reproduction before and after clearcutting. ACORn comprises two modules that simulate the development of the two primary sources of reproduction in that ecosystem: stump sprouts and advance reproduction. One module simulates the development of advance reproduction and the other the development of stump sprouts. Each module, in turn, contains models for estimating future heights, diameters, and survival of individual stems by species. The probability of survival of individual stems of both advance reproduction and stump sprouts, from preharvest to a specified future stand age, is estimated from initial tree size and site factors. Species-specific models estimate future tree heights and diameters from similar predictors. The predictive models, in turn, facilitate the generation of future diameter and height distributions of surviving reproduction including stump sprouts and advance reproduction by species. Projections for hickory, flowering dogwood, blackgum, and sassafras also can be obtained.

In application, preharvest inventories of the overstory and advance reproduction provide input to survival and growth models that generate diameter distributions 21 years after clearcutting. At that age, mean stand diameter averages 3 in. d.b.h. The diameter distributions then can be used to summarize stand characteristics, such as basal area per acre, stems per acre, and percent stocking by species. From this stand summary, the adequacy of future stocking can be assessed and used to develop appropriate silvicultural prescriptions. The resulting diameter distributions also can be used as input into growth and yield simulators such as TWIGS.

PREDICTING REGENERATION QUALITY

Quality of reproduction is commonly defined in terms of the acceptability of growing stock. Before adequacy of regeneration potential can be assessed, it is necessary to define acceptable growing stock, which requires a consideration of species and tree characteristics. Commonly used tree characteristics are height, diameter, and crown class. Although a qualitative characteristic, crown class is a concept with which most foresters are familiar. It is a widely used descriptor of trees because it facilitates visualization of a tree's social status more easily than diameter or height measurements, *per se*. For example, the definition of acceptable growing stock may be limited to certain species and trees that occupy only codominant and dominant crown classes. ACORn solves that problem by projecting future diameter and survival of individual trees by diameter and crown classes to stand age 21.

Some foresters may consider only codominant and dominant trees as acceptable growing stock. Others may consider trees that are intermediate or larger as acceptable. To integrate this decision into the regeneration model, a threshold tree diameter is defined that classifies trees into one of the two user-defined crown class categories: acceptable or unacceptable. When acceptable growing stock includes only codominant and dominant trees, tree diameters equal to or greater than 3.8 in. are classified as codominant or dominant at stand age 21. When acceptable growing stock is defined as trees that are intermediate or larger, trees with diameters less than 2.6 in. are classified as suppressed, and those with larger diameters are classed as acceptable growing stock. In this way, ACORn incorporates crown class to project twenty-first-year diameter distributions.

Regeneration Surveys

Data from preharvest inventories of the overstory and advance reproduction provide the necessary input for ACORn projections of future stand composition and structure. To inventory a stand, the overstory (trees 1.6 in. d.b.h. and larger) is sampled separately from the advance reproduction (trees less than 1.6 in. d.b.h.). Because ACORn is an individual tree model, it projects the survival and growth of single trees and then expands this to a per-acre basis in the form of stand tables. The model thus can accommodate a variety of sampling designs.

Fixed-area or variable-radius plots can be used to inventory the overstory. Sander and others (1984) recommended that the overstory be sampled on 1/20-acre plots in their regeneration guide. Small fixed-area plots were recommended for inventory of advance reproduction. The model of Sander and others (1984) requires that advance reproduction be inventoried on 1/735-acre plots. The choice of sample plot size and number should be done on a stand-by-stand basis. There are numerous sampling techniques that can be used to design efficient and effective inventories (e.g., Freese 1962).

In general, the more variation there is in species composition, tree size, and the spatial distribution of trees, the more sample plots that are needed. It is usually best to sample a large number of small plots where stand variation is great than it is to sample fewer large plots. A common rule-of-thumb is to inventory at least 30 plots regardless of stand size. The upper limit to the number of plots depends on (1) constraints such as budget, crew size, and timeframe; (2) intended use of simulation, i.e., forest planning or stand prescription development; (3) amount of stand variation; and (4) desired level of precision. Plots should be distributed randomly or systematically throughout the stand.

ACORn requires an inventory of the overstory including species, d.b.h., site index (black oak, base age 50), and stand age. When the overstory is even-aged, an average stand age can be substituted for individual tree age. For advance reproduction, the required inventory includes data on species, basal diameters, and heights of reproduction, slope position (upper, middle, or lower), and aspect. A computer program is available to facilitate application of the model.

SUMMARY

The structure of regeneration models is determined by the sources of reproduction and by the biotic and abiotic factors that affect population dynamics of the ecosystem being modeled. Sources of reproduction include new seedlings, advance reproduction, and sprouts from the cut stumps of overstory trees. The micro-environment (e.g., light, temperature, and soil moisture) influences the development of reproduction. Aspect, slope position, elevation, and site index are commonly used to express the integrated effect of micro-environment on reproduction. In some upland oak ecosystems, wildlife such as deer may adversely affect stand regeneration potential. Interference species such as ferns, fire cherry, red maple, and flowering dogwood may dominate the site following harvest, thereby reducing the regeneration potential. The importance of these factors in influencing regeneration potential varies among regions. Thus, regeneration models should be developed for specific regions.

Hardwood regeneration models are available today for individual species or forest types in the United States. Several examples have been discussed in this paper. SILVAH incorporates predictions of regeneration success of northern hardwoods in selection of appropriate silvicultural prescriptions. A regeneration model also is available for northern red oak in the Southern Appalachians. ACORn generates future diameter and height distributions of reproduction (stump sprouts and advance reproduction) for the Missouri Ozarks. The resulting distributions simulate, by species and reproductive origin, the regeneration process from preharvest to the end of the regeneration period (stand age 21). Characteristics of the new stand then are summarized in the output so they also can be used as input into growth and yield simulators such as TWIGS. Resource managers thus can predict, before harvest, future stand development following final harvest. Preharvest inventory of the parent stand and site conditions is a necessary first step to planning appropriate silvicultural activities.

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Prediction of Oak Regeneration in Bottomland Forests

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ABSTRACT

In 1980 Johnson presented a preliminary method to evaluate oak regeneration potential in southern bottomland hardwood forests. The method evaluates regeneration potential by assigning points based on number and size (height class) of advance regeneration and sprout potential of stumps from severed trees. The method appears promising for evaluating regeneration potential but has not been tested under operational conditions. Research is currently underway to test the method and make refinements if necessary. Current data indicate that 78 percent of plots evaluated as adequately stocked before harvest were still adequately stocked with desirable regeneration following harvest. Preliminary results showing seedling mortality, seedling growth by size (height and root collar), and logging losses indicate that improvements to the method can be made through modifications of point assignment.

INTRODUCTION

Through continuing and widespread research efforts, there now exist predictive models to evaluate the potential for oak regeneration success prior to harvest of upland hardwood stands (Dey 1991, Loftis 1990, Marquis and Bjorkbom 1982, Sander and others 1976, Waldrop and others 1986). The foundation underlying the use of these evaluation techniques is that, to successfully regenerate oaks, there must exist adequate numbers and/or size of advance oak regeneration prior to harvest.

The above mentioned predictive models (Dey 1991, Loftis 1990, Marquis and Bjorkbom 1982, Sander and others 1976, Waldrop and others 1986) were designed for use within specific physiographic regions and application elsewhere should be approached with caution. A more complete description of these regeneration techniques will be given by their respective authors elsewhere in these Proceedings.

The harvest and regeneration of bottomland hardwoods has been a fascinating subject for many years. Hardwood regeneration in the bottoms is often easy, but almost as often, the successful regeneration of bottomland hardwoods, especially oaks, can be very difficult. Forest land managers have for many years needed to predict when, where, and how their hardwood regeneration efforts would be successful. In 1980, a hardwood regeneration prediction model for bottomland hardwoods was devised (Johnson 1980). The purpose of this paper is to examine how the Johnson method can be used to predict oak regeneration, and based upon preliminary testing, how the procedure can be improved.

The regeneration prediction method when used within the constraints discussed later has been found to be both useful and reliable. However, we should emphasize that the expected results for any given situation are based upon a combination of empirical results and the senior author's experience. The authors believe that with on-the-ground experience many users can adapt the procedure to more closely fit their needs and conditions.

For bottomland oaks, our target species in this paper (table 1), we know, for example, that acorn production varies considerably among species, years, and phenotypes. Good acorn crops may be 3 to 5 years apart. Acorns are often utilized by wildlife after seedfall and a good seed crop may not produce a good seedling crop. In some years and on some sites acorns of bottomland oaks may be protected from birds and animals when they drop into or are soon covered by water that stays in the forest until early in the growing season. Duration of the water cover is important. If the water leaves before germination, acorns will be exposed and eaten; if the water stays into the summer, acorns will rot. Water that recedes during the germination period usually results in several days of moist seedbed that allows germinating acorns to establish seedlings. Without surface water and given that radicles cannot penetrate a dry, hard surface soil, acorns that roll into soil cracks or that are buried by animals or birds (Deen and Hodges 1991) have the best chance to establish a new seedling.

Oak seedling populations may be large in numbers beneath the crowns of mature oak trees; e.g., Johnson (1975) found up to 100,000+ nuttall oak (*Quercus michauxii* Nutt.) seedlings per acre in the Mississippi Delta. Red oak seedlings in full shade will normally grow approximately a foot in height during the first year, and most die within 3 years. Those that receive 2 hours of direct sunlight daily may survive beyond 3-5 years, but grow only an inch or so in height annually.

Table 1—Ranking of desirable species; i.e., oaks and ash, based on their percentage of the total number of stems initially sampled over all study plots in east central and south Mississippi

Common name of species	Number of stems	Percentage of total
Willow oak	1,311	45.30
Water oak	799	27.60
Green ash	197	6.80
Cherrybark oak	193	6.70
Overcup oak	168	5.80
White oak	108	3.70
Diamondleaf oak	47	1.60
Swamp Chestnut oak	31	1.10
Shumard oak	20	.70
Southern Red oak	12	.40
Nuttall oak	5	.20
Northern Red oak	1	.03
Total	2,892	99.93

Oaks that die back and resprout almost always start in small openings where there is enough sunlight to allow for 5-10 ft. of height growth before the overstory closes and direct sunlight is shut off. These larger trees have a well-developed root system that will support rapid shoot growth when the overstory is removed.

Once released, mortality of oak seedlings is most likely to occur the first year. Flooding is a likely cause of mortality, but exposure to frost may result in dieback or mortality (McGee 1988). Thereafter, at least through year 10, three of four oaks should survive even with overtopping competition. With only side competition, oak regeneration will continue growing upward and have a good chance to eventually become dominant.

Height growth of released seedlings ≤ 1 ft. tall is slow for the first 5 years, whereas taller advanced reproduction and stump sprouts grow rapidly from the start. For bottomland oaks, stumps up to 12 in. in diameter have a good chance of producing sprouts that are acceptable regeneration; larger stumps usually do not produce sprouts, or if they do, the sprouts are likely to die. Because of the length of time necessary to produce quality oak lumber, oak stems will grow beyond a threshold-diameter capable of producing many, if any, stump sprouts. Also, the total number of sawlog-sized oak stems per acre in a mature, bottomland hardwood stand would be low enough to discount these stumps as providing adequate stocking of oak sprouts for regeneration purposes. Sawlog-sized oak, then, can be mostly discounted as an adequate source of sprouts from which to restock the newly developing stand (Johnson 1975).

THE PREDICTION MODEL

The method proposed by Johnson (1980) is based on the silvical characteristics of the species as discussed above. It is a numerical evaluation of regeneration potential which emphasizes the size (height class) and numbers of advance regeneration and the contribution of stump sprouts to regeneration potential (form 1). Weights and points given various regeneration components are based on the senior author's 35 plus years of research experience. The following procedures are used in the evaluation process:

1. The sample plot is a circular 1/100th acre. This plot size will accommodate large trees (because stump and root sprouts are considered as reproduction) as well as seedlings and saplings. The selected size also provides an easy blow-up factor.

2. One point for each tree ≤ 1.0 ft. tall. Mortality is high among such trees because they are only a year or two old and are not well established. In fact, all trees ≤ 1.0 ft. tall may die if overstory removal is delayed for more than a year. However, a few small trees may be older, well established, and likely to survive several years with or without overstory release. The one point per tree is an attempt to balance the survival potential of young and older, established trees. Young or old, small trees are not very competitive.

3. Two points for each tree 1.1 to 2.9 ft. tall. Trees of this size are older than 1 year and have a well-developed root system that will aid survival and provide for height growth. Trees in this size class are more competitive than trees ≤ 1.0 ft. tall, but less competitive than those ≥ 3.0 ft. tall.

Date________________

Plot number________________

Location________________

Form 1

REPRODUCTION INVENTORY

Circular 1/100-acre plot (11.8' radius)

Points per tree and number of trees by species and size class

	Height (feet)						DBH (inches)								
	<1.0		1.0-2.9		3.0+		2-5		6-10		11-15		16-20		
Species	Pts.	No.	Pts.	No.	Pts.	No.	Pts.	No.	Pts.	No.	Pts.	No.	Pts.	No.	Tot. Pts.
Ash	1		2		3		3		3		2		1		
Red oaks															
________	1		2		3		3		2		1		0		
________	1		2		3		3		2		1		0		
________	1		2		3		3		2		1		0		
White oaks															
________	1		2		3		3		2		1		0		
________	1		2		3		3		2		1		0		
Hickory	1		2		3		3		3		2		1		
Sweetgum	1		2		3		3		3		2		1		
Blackgum	1		2		3		3		3		2		1		
Elm	1		2		3		3		2		1		0		
Yellow-poplar	1		2		3		3		2		1		0		
Maple	1		2		3		3		2		2		0		
Sugarberry	1		2		3		3		2		1		0		
Persimmon	1		2		3		3		2		1		0		
Other															
________	1		2		3		3		2		1		0		
________	1		2		3		3		2		1		0		

Stocked - 12 points or more

Total points this plot____________

Yellow-poplar or sycamore seed tree within 100 feet	+6
Seedbed bare	+2
Seedbed weedy	-2

4. Three points for each tree ≥3.0 ft. tall but less than 5.5 in. d.b.h. Trees are able to grow into this size class while in small openings but not in full shade. Thus, the trees are several years old, have large root systems, are almost certain to survive an overstory harvest even if their tops are broken off, are good stump sprouters, and should have rapid post-harvest height growth. Trees in this class make good competitors.

5. Two points for each tree 5.6 to 10.5 in. d.b.h. A high percentage of stumps from trees in this size class will produce competitive sprouts that survive and grow very well. Usually no more than three stumps of this size will occur in a 1/100th-acre plot.

6. One point for each tree 10.6 to 15.5 in. d.b.h. Not many of these relatively large stumps will produce acceptable, competitive sprouts. No more than one or two trees of this size class will occur in a 1/100th-acre plot.

7. Twelve points per plot is considered high enough to ensure adequate regeneration following harvest. The points could represent 12 trees per plot or 1,200 trees per acre that are a foot or less in height, 4 trees per plot (400 per acre) 3.0 ft. tall to 5.4 in. d.b.h., or from any combination of trees equalling 12 points. Although natural stands may start with 20,000 plus trees per acre, they will thin to fewer than 400 crop trees per acre at minimum commercial size (6 in. d.b.h.). The 12 points is a judgment call, believed conservative, and should be considered only as a general guide.

A possible limitation of the guide is that it does not recognize seedlings which germinate after harvest. Oak seedlings may become established after harvest and become an important part of the regenerated stand, but, this model does not provide for such a happening. If advance regeneration is lacking and if there are no oak stumps of sprout-producing size, this model predicts zero oaks in the regeneration stand. Also, the total number of stocked plots needed for successful regeneration of a given tract is still questionable. It appears that at least 60 percent of the total plots must be stocked ($\geq$12 points) and well distributed over the tract to ensure successful regeneration.

Testing the Prediction Model

Research is currently underway to test and evaluate the regeneration prediction method described herein.

Study areas 10 acres and larger were located mainly in the floodplain of minor streambottoms. Permanent 1/100th-acre circular plots were systematically located within each study area.

Woody vegetation was placed into one of three size classes and identified as either desirable (oaks and ash) or undesirable (all other woody species).

To develop a priority rating for predicting regeneration potential of oaks and ash, desirable stems placed in seedling or sapling categories were identified and tagged. Stems could be identified from year-to-year, enabling development patterns to be detected and related to preharvest size.

Desirable and undesirable vegetation was identified by species and placed in the appropriate height class. In addition, permanent trees were selected and measured for root collar diameter. All woody vegetation was designated as to origin class; i.e., sprout or seedlings. Desirable and permanent sample trees were noted as to occurrence of top die-back, insect or disease damage, damage due to harvesting operation, and subjectively rated as to competitive status, i.e., free-to-grow, medium competition from surrounding vegetation, or overtopped.

Regeneration was evaluated for each plot according to Johnson's (1980) technique (form 1) before harvest and after each remeasurement to determine the adequacy of the technique and, if needed, make adjustments to the guide to more accurately predict regeneration success.

Following harvest, a resurvey of the plots was conducted to quantify logging damage, if any, to permanent sample trees and to the site that would adversely affect subsequent vegetative composition and growth and development of the future stand. At this time, a survey was taken of the number of light-seeded species occurring within 200 ft. of each plot. Seedlings from these fast-growing, intolerant species could ultimately suppress the development of desirable species, oaks and ash, in the future stand.

Other factors affecting stand development (i.e., high water, severe vegetative competition, etc.) were recorded at each plot visit. Also, newly germinating oak or ash species were marked with a combination of colored expansion rings, designating a particular height class and a particular year of germination, so further development can be followed.

RESULTS AND CONCLUSIONS

There were 118 plots established on nine bottomland hardwood tracts in east central and south Mississippi. The tracts used in the study were logged between August and September of 1989 and 1990. Table 1 gives the total number of desirable stems, by species, that were initially sampled in this study.

Based on form 1, the sampled stands shown in table 2 exhibit differing trends of stocking success following harvest. The decline in percentage stocking of those stands shown in table 2 can be attributed to the high degree of mortality, due to logging, of oak regeneration ≤1.0 ft. tall (table 3). Seedlings ≤1.0 ft. tall accounted for the bulk of points assigned to plots within these stands before

Table 2—The use of Johnson's (1980) evaluation technique (form 1) to predict percentage of plots adequately stocked, with oaks and ash, per tract before and after harvesting

Tract	Percent plots stocked Preharvest	Percent plots stocked Present	Years Since Harvest
Noxubee Refuge			
U1DLR	55.6	33.3	2
U3KTR	60.0	40.0	2
U2TPR	68.8	68.8	2
U1KTR	50.0	50.0	2
U3CGR	60.0	40.0	3
U1CGR	100.0	100.0	3
U4KTR	55.5	77.8	3
Scott Paper			
#1	.0	.0	1
#2	80.0	30.0	1

Table 3—Percent mortality among permanent sample seedlings of desirable species, i.e., oaks and ash, due to logging damage

	Seedling height classes (ft.)		
	0.1-1.0	**1.0-2.9**	**≥3.0**
Percent (# Dead/Total #)	62.9 (166/264)	40.1 (78/192)	41.1 (69/164)

harvest, and the loss of these seedlings following harvest resulted in lower point totals for these plots. Accordingly, form 1 may need to be revised to reflect the need for greater numbers of regeneration ≤1.0 ft. tall for adequate regeneration when this is the only source of regeneration.

The one stand (table 2) that showed an increase in stocking percentage following harvest contained a majority of desirable stems >1.0 ft. tall before harvest. Desirable stems, 1.1-2.9 ft. tall and ≥3.0 ft. tall, have a much greater chance for survival (table 4). Also, in this stand individual stems have progressed in height class, increasing the points allocated to that particular seedling, and likewise increasing the point total for that plot.

Table 4—Percent survival rates of seedlings of desirable species, i.e., oaks and ash, by height classes 1 and 2 years after harvest

Years after	Seedling height classes (ft.)		
harvest	**0.1-1.0**	**1.0-2.9**	**≥3.0**
1	25.0	54.4	63.7
2	9.8	46.5	63.7

Four stands remained constant as far as percentage stocking is concerned. Two stands appear adequately stocked, one stand is borderline, and one stand is considered nonstocked.

One point we are trying to determine is the cut-off point where a stand should be classified as suitable or not for regeneration based on initial stocking. Twelve points is now considered the threshold. However, some plots that do not make 12 points contain several stems that are large enough to successfully compete for growing space and some day become a component of the overstory. If that is the case plots containing less than 12 points but containing larger regeneration may be adequately stocked. Observation of stand development over time is needed to clarify this point.

Logging damage following harvest was assessed using the permanent sample trees located within each plot. Saplings and/or seedlings were categorized as to the extent of logging damage, i.e., intact, bent, broken, missing, or dead. Stems that were classified with severe logging damage (i.e., broken, missing, or dead) which were dead at the next remeasurement were assumed to have died as a result of logging damage (table 3). Some stems in the sapling class, 2.0-4.4 in. d.b.h., were pushed completely out of the ground exposing their rootstocks and ultimately resulting in death. Loss of this type of regeneration can be reduced by chainsawing of saplings prior to harvest.

Development of oak regeneration after clearcutting followed similar patterns to those reported in other regions (Loftis 1983, Sander 1972) where large advance regeneration exhibited better survival than small advance regeneration. Survival data (table 3) indicate that desirable seedlings $\leq$1.0 ft. in height cannot be counted on to provide many stems to the newly regenerated stand. Also, field data and observation showed that these seedlings $\leq$1.0 ft. tall which did survive had large root collar diameters, indicating that such stems had probably died back and resprouted several times. The larger rootstocks enabled these smaller stems to produce a vigorous, competitive sprout.

Stems in the 1.1-2.9 ft. and $\geq$3.0 ft. height classes exhibited much better survival rates following harvest (table 3). It appears these two size classes will contribute the bulk of the stems to the new regeneration stand.

One growing season after harvest, 162 new oak and ash germinants, $\leq$ 1.0 ft. tall, and seven new ash germinants, 1.1-2.9 ft. tall, were found. Forty percent of the seedlings $\leq$1.0 ft. tall survived their first growing season while six of the seven ash germinants 1.1-2.9 ft. tall survived. In the second year following harvest there were 22 new germinants of oak and ash which were $\leq$1.0 ft. tall, and six new ash seedlings, 1.1-2.9 ft. tall. They have yet to be evaluated after a full growing season so their fate is undetermined. However, most research indicates that contribution of the new seedlings will be insignificant and that advance regeneration will provide the bulk of the stems to the new stand.

Seedling height growth was as follows: seedlings $\leq$1.0 ft. tall averaged 7.7 in. tall preharvest. One year after harvest, average height for these seedlings was 10.9 in., and after 2 years average height was 17.7 in. Seedlings 1.1-2.9 ft. tall, similarly, realized a 10.0-in. increase in average height over 2 years, growing from 20.6 to 30.6 in. However, the desirable stems in the $\leq$1.0 ft. and 1.1-2.9 ft. height classes are competing with desirable stems from the $\geq$3.0 ft. height class, as well as undesirable stems, for growing space in the newly developing stands. A number of stems in these height classes are free-to-grow and may eventually achieve a dominant position.

Seedlings $\geq$3.0 ft. tall before harvest showed a decrease in average height after the first growing season, from 82.2 in. to 47.3 in. This was primarily a result of logging damage, but there is evidence that exposure to low temperatures in the spring following release can result in top die-back (McGee 1988). After the second year, average height increased to 60.1 in. This is a result, mainly, of the vigorous sprout growth of these larger stems of advance regeneration. Some stems were also able to respond rapidly to the increased light conditions created by clearcutting. A majority of these stems are already in a free-to-grow position and have assumed a dominant position in the new stand. Their vigorous, rapid height growth may assure a dominant crown position as the stands develop.

Preliminary data show that stump sprouting for trees >1.5 in. d.b.h. were as follows: 45.6 percent for the 2.0-5.0 in. d.b.h. class, 42.9 percent for the 6.0-10.0 in. d.b.h. class, 33.3 percent for the 11.0-15.0 in. d.b.h. class, 50.0 percent for the 16.0-20.0 in. d.b.h. class (only two trees in this class), and the >20.0 in. d.b.h. class had no sprouting. The trend seems to be a decrease in sprouting with an increase in tree (stump) size as shown in other studies (Johnson 1977, McQuilkin 1975). Also, as trees increase in size their numbers decrease on a per-acre basis and, coupled with their reduced sprouting ability, further reduces their contribution to the regeneration stand.

RECOMMENDATIONS

A model that predicts regeneration success was developed for southern bottomland hardwood forests, but should be suitable throughout the Southeastern United States. It is applicable only where complete overstory harvest is intended, meaning that all trees 2 in. d.b.h. and larger are cut from an area sufficient in size to allow full sunlight to reach the ground.

Because the number and vigor of understory oaks change rapidly, prediction by the model is useful for 1 year only. If harvesting is delayed, the stand should be resampled.

Based on experience it appears that one sample plot per acre might be needed for tracts under 50 acres, whereas for larger areas one plot per 2 or 3 acres may do. Stratified sampling is suggested where different stand conditions can be recognized and delineated. A systematic sampling scheme is practical and adequate.

The model is not refined enough to predict which tree, among the many mixed species, may eventually dominate. But, in the same growth environment (same growing space and micro-site) a tree with three points is much more likely to survive and compete than a 1-point tree. Growth environments differ, however, even over a foot or two in space, so there may be considerable variation in the way one 3-point tree compares to three 1-point trees in long-term development among competitors.

A point total of less than 12 per plot doesn't necessarily mean the sample area will not regenerate satisfactorily, but it does signal caution. For example, it seems likely that if oaks contribute only two points per plot, then they will not be a major part of the new stand. On the other hand, large advance regeneration appears highly likely to survive the rigors of harvesting to become a component of the new stand. Possibly, only two large stems per plot may be necessary to ensure successful regeneration.

A plot with more than 12 points, made up mostly of seedlings ≤ 1 ft. in height, may not be adequate for regeneration due to heavy mortality among seedlings in this height class. More seedlings ≤ 1 ft. in height may be needed to qualify plots as adequately stocked.

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Decision-Making for Natural Regeneration in the Northern Forest Ecosystem

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ABSTRACT

Failure to obtain prompt regeneration of desired species after a harvest cut can leave a stand unproductive for many decades, cost excessive amounts to reclaim through artificial means, and severely limit the suitability of the stand for a wide range of forest values. But prescribing silvicultural treatments that ensure successful regeneration most of the time is a difficult task.

Forest managers need to consider all the many factors that could affect regeneration success, weigh the many available silvicultural techniques available to accomplish the task, consider the characteristics of the particular stand under consideration, and make an informed decision that is most likely to achieve the desired conditions. In this paper, decision-making procedures are described that provide a systematic way to analyze stand potential and prescribe regeneration treatments. In the Allegheny region where the system has been used extensively, successful regeneration has been obtained in over 90 percent of the stands harvested, compared to only about 50 percent prior to development of this system. The procedures can be adapted for use in any geographic region or forest type.

INTRODUCTION

Natural regeneration of oaks is difficult to obtain in the northern forest ecosystem, just as it often is in most other parts of the oak range. To the common problems resulting from infrequent acorn crops, acorn depredations, slow juvenile oak seedling growth, and intense competition from other fast-growing plants, northern ecosystems add additional obstacles. Many oak stands in the north are found on sites better adapted to northern hardwoods, and the natural tendency is for them to revert to northern species now that fire and grazing have been removed as factors favoring the oaks. In addition, many northern ecosystems support excessive deer populations that make regeneration of any woody species difficult.

Research now underway is providing much information that will help us develop silvicultural procedures to perpetuate the oaks. We hope that this research will also define the range of sites where the battle to maintain oaks—rather than allowing conversion to northern species—is economically and ecologically feasible. There is still a long way to go before reliable procedures to regenerate oak on good northern sites are available, but progress is being made.

One point is already quite clear, however: there will be no simple or universal treatment that guarantees consistent oak regeneration across the wide range of stand and site conditions found throughout the oak region. Instead, success will depend upon the careful prescription of treatments tailored to each individual situation. Stand and site conditions and all potential obstacles to oak regeneration will need to be evaluated systematically before a specific treatment is recommended. This decision-making process will require considerable knowledge and judgment on the part of the forest manager.

About 12 years ago, a systematic procedure for making silvicultural prescriptions for individual cherry-maple, northern hardwood, and oak stands in the Allegheny region was developed, and that procedure has been refined as new knowledge has accumulated. This stand evaluation and prescription process, known as the SILVAH system (Marquis and others 1992, Marquis and Ernst 1992), has been widely used in the Allegheny region, where it has helped forest managers consistently prescribe successful treatments in areas where deer browsing and other factors had traditionally prevented regeneration. That basic decision-making procedure is now being expanded to cover other forest types and geographic regions of the Northeastern United States (Marquis 1991a). In this paper, decision-making procedures we've developed for regeneration prescriptions in the Northeast are described. The process could be applied anywhere in the oak region if decision criteria appropriate to the geographic area are substituted for the Northeastern criteria. These decision-making procedures are also being expanded within the Northeast Decision Model for purposes beyond timber production. The successful establishment of new young trees after disturbance is important for all values derived from forests. Although the decision criteria may differ, the same data and decision procedures may be used in making regeneration decisions where wildlife, aesthetics, water, or other forest values are the management goal.

THE DECISION-MAKING SYSTEM

The decision-making system involves the use of (1) a set of decision charts, (2) specific criteria to be used in making each decision, and (3) data on which to determine the condition or characteristics of the stand in question.

Decision Charts

Decision charts are simply an outline of the decision-making process. All of the factors known to influence regeneration are included, and these factors are arranged in an order that systematically determines that stand's suitability for particular silvicultural techniques. As implemented in SILVAH and the new NE Decision Model, these are dichotomous charts that ask a series of yes/no questions about the stand and site under consideration.

A portion of the new NE Decision Model chart for even-age silviculture serves as an example (charts 8, 8.1, 8.1a, 8.1b, and 8.1z, from Marquis 1991b). Other portions of the NE charts deal with intermediate even-age culture and with other silvicultural systems.

In these charts, specific symbols are used to denote their function in the decision chart. Circles denote the start of the process. Five-sided boxes are connecting symbols that route you to (or from) other charts. Arrows denote the sequence of travel within the chart. Horizontal lines with a short question above the line represent the main decision points in the chart. Rectangular boxes at either end of the decision question represent the possible answers—in this case, either "Yes" or "No." Ovals represent prescriptions, or recommended treatments; once you reach an oval, you have completed the decision process for that stand. Note in the legend for chart 8 (next page) that some prescription ovals are shaded or cross-hatched, indicating different degrees of confidence in the recommendation and/or various levels of investment required.

Target Species Target species, as used in the Prescription Charts, refers to the species or species group that you wish to reproduce and/or manage for. For example, you may choose to manage for the oaks, or for white pine, or all northern hardwoods. If the prescription derived from the charts requires planting or protection against browsing, or other unacceptably expensive treatments, you may wish to redefine the target species to include a broader group of species already present on the site, then re-determine the prescription to evaluate that alternative.

Yes or No — All decision criteria in the NE Decision Model are expressed as Yes or No answers to the questions asked at each decision point in the prescription charts. Amounts, levels, or values that constitute a Yes or No answer are defined in the decision criteria tables. There is a separate table for each forest type.

○ These prescriptions generally produce the desired results in the opinion of the NE Decision Model experts. They require no cash investments, and are highly recommended.

░ These prescriptions generally produce the desired results, but require an investment. If such investments meet your organization's economic criteria, we recommend them. If not, we recommend that no cutting be done in this stand. In the case of regeneration prescriptions, stands generally will not reproduce without the recommended treatment. For timber goal 4 (maximize timber value) these treatments will be recommended if you choose to maximize income, but not if you choose to maximize internal rate of return.

▨ These prescriptions will not always produce the desired results, and they are quite expensive. The experts who developed the NE Model do not recommend them under either option of timber goal 4, but they are shown in case you feel you want to do something. We generally recommend that you devote your attention to more productive stands, and avoid expenditures in these difficult ones.

An alternative to both shaded and cross-hatched prescriptions is to shift your regeneration objective to less difficult target species.

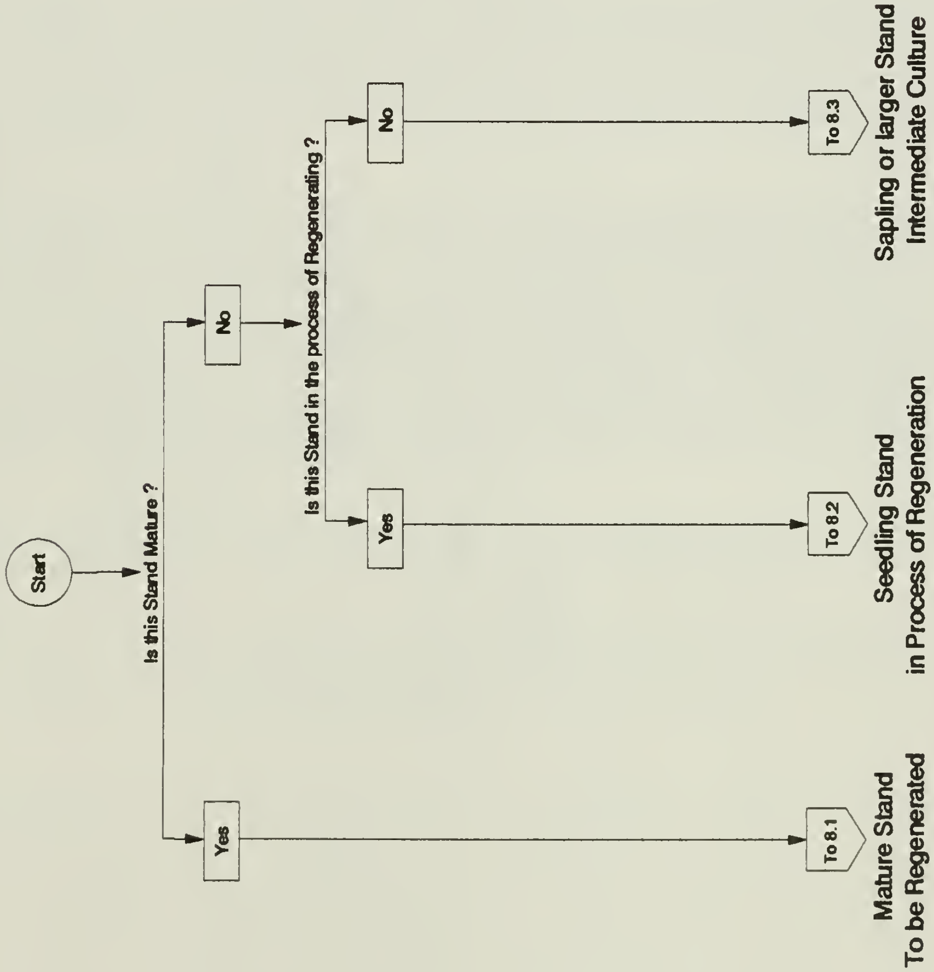
Legend—Prescription Charts.

Note also that the charts are divided into zones by horizontal lines, and that there is a decision question on the left edge of the chart for each of these zones. The zones and their associated questions are included only to make the charts easier to understand.

Portions of the decision process that led to chart 8 are omitted because they do not involve regeneration considerations. However, to arrive at chart 8, you would have had to determine that even-age silviculture was the appropriate silvicultural system to use in this management unit. In the NE Decision Model, eight separate silvicultural "systems" are recognized, of which traditional even-age silviculture is number eight. This decision on the overall silvicultural system to be used is based primarily on the specific management goals selected, plus the forest type.

The eight systems in the NE Decision Model are viewed as a continuum on two different directions: intensity of disturbance and frequency of disturbance. The even-age system described in chart 8 is at one end of each continuum—intense but infrequent disturbance. Of course, the system selected is very important in

Chart 8 -- Even-age Silvicultural System

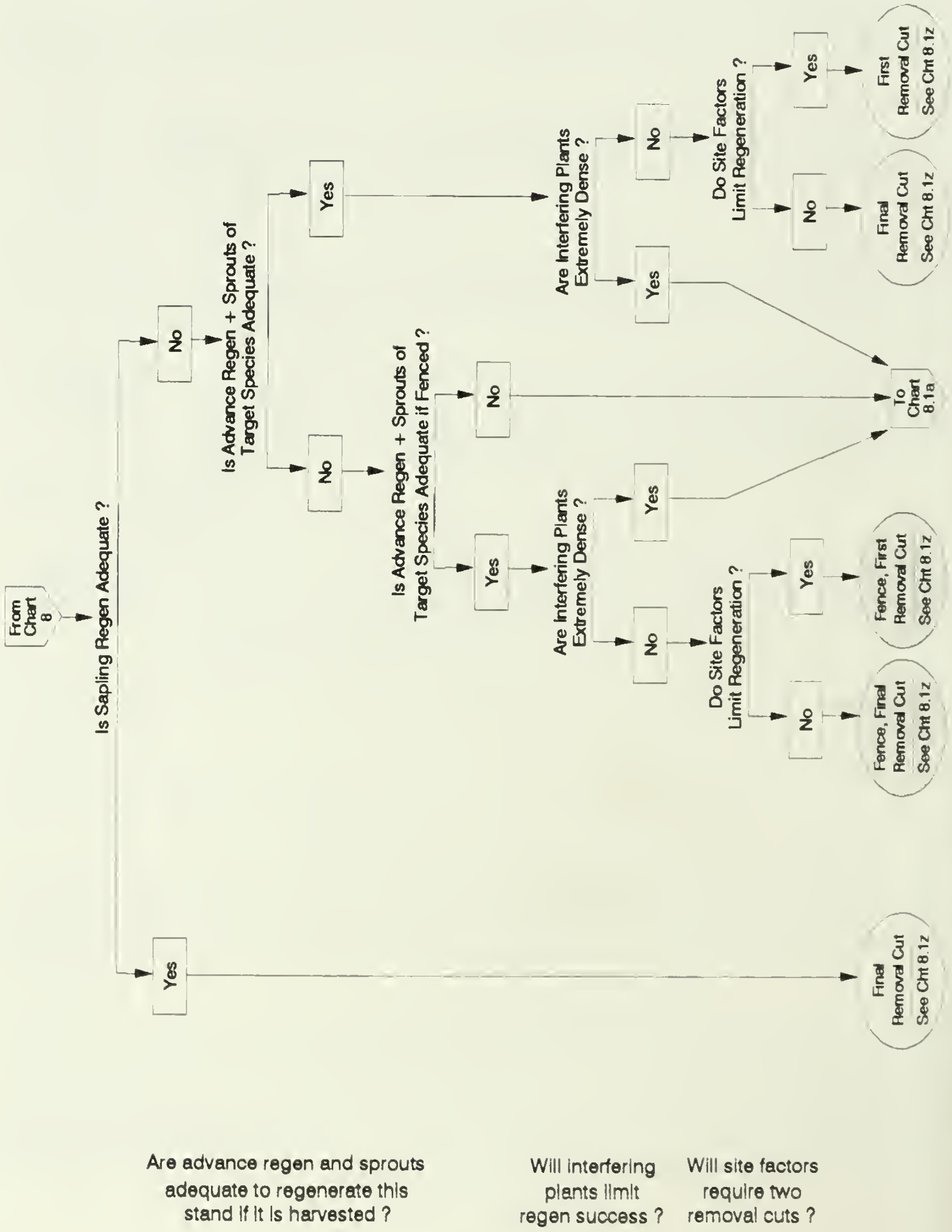


In what stage of development Is this stand ?

determining which of the potentially desirable species are likely to succeed under a prescription made by the model. Tracing a few prescriptions through the decision chart will illustrate its use.

The first chart in this series, chart 8, has only one zone, and its purpose is to determine the stage of development of this stand. If the stand is mature and ready to be regenerated, you will be routed to the 8.1 section of the chart. If regeneration treatments have already been applied, but the stand is still in the process of regenerating, you will be routed to the 8.2 section of the chart where the need for weeding, protection against animal depredations, and similar matters

Chart 8.1 -- Mature Stand to be Regenerated
Possible Removal Cut



are considered. If the stand is in the sapling or larger stage but not yet mature, you will be routed to section 8.3 of the chart where the need for intermediate thinning and similar treatments will be evaluated.

Starting at the top of chart 8, the first decision point we reach contains the question: "Is this stand mature?" If we answer "Yes," we are routed to chart 8.1, which is the beginning of the section on regeneration prescriptions.

Remember that the decision charts are simply the outline for the decision process. To decide whether to answer the question about stand maturity "Yes" or "No,"

we'll need specific criteria on what constitutes stand maturity. Those criteria will be covered later.

At the top of chart 8.1, the five-sided box completes the connection from the previous chart. As the title of chart 8.1 indicates, it will consider the possibility that a removal cut is appropriate in this stand. The first zone deals with the adequacy of existing advance regeneration plus expected sprouts to regenerate the stand if harvested. There are three specific decision points or questions in this zone.

The simplest case involves those stands that already have regeneration of sapling size established in adequate amounts to form a new stand. Such a stand might have resulted from a heavy cut 10 to 25 years earlier, perhaps a diameter-limit cut or the second cut of a three-cut shelterwood. All that needs to be done is to remove the remaining overstory of the old stand to release the new stand. This prescription is reached if you answer "Yes" to the first decision question, "Is Sapling Regen Adequate?" Again, the criteria by which you decide whether or not sapling regeneration is adequate will be discussed later.

If sapling regeneration is not adequate, follow the route through the "No" box to the question "Is Advance Regen + Sprouts of Target Species Adequate?"

A "Yes" answer here moves us through the first zone to additional zones that deal with interfering plants and site limitations. A final removal cut, or clearcut, will be recommended only if interfering plants and site are not limiting.

If interfering plants are dense, removal cutting is not likely to provide satisfactory regeneration of the desired species, and you are routed to chart 8.1a where alternative techniques are considered. Interfering plants here include any plants that may interfere with successful regeneration of desired or target species. These may be herbaceous plants like fern and grass, woody plants of no commercial timber value like striped maple, dogwood, and sassafras, or commercial tree species such as yellow-poplar and red maple that outgrow desired oaks species under full sunlight. The criteria for evaluating these interfering plants deal with both those plants present in the understory before cutting and those present in the forest floor as dormant seed banks.

If certain site factors alone are limiting to regeneration, the recommendation will be for the removal harvest to be done in a sequence of two cuts that ameliorate the site limitations (wet or extremely rocky surface soil), with the first removal cut to be made now. Retaining 35 to 40 percent overstory density until the advance seedlings and sprouts grow to small sapling size and have established roots in deeper soil layers has been found effective in maintaining a transpiration pump to avoid saturated conditions on wet sites, and in stabilizing the surface organic soil on rocky areas, as opposed to single-cut removals which accent the soil limitations.

Going back to the first zone, a "No" answer will lead to a repeat of the question about adequacy of advance regen + sprouts, assuming the area is fenced against deer. In areas of high deer population, the numbers of advance seedlings and sprouts needed to assure successful regeneration is very high, since deer browsing destroys many of them. A fence to exclude deer has the effect of reducing the numbers of advance seedlings and sprouts needed, and may permit removal cutting to occur where it would otherwise not be feasible. This section of chart 8.1 is identical to that discussed above, except that any prescription for a removal cut now includes erection of a deer fence as well.

If advance regen + sprouts of target species are not adequate even if fenced, you are routed to chart 8.1 where alternative techniques to encourage advance regeneration establishment are considered.

The remaining charts work in much the same way, but deal with other circumstances.

Chart 8.1a considers the possibility that a shelterwood sequence will permit advance seedlings to develop. Decision points here include evaluations of interfering plant density, overstory density or shade level, seed source availability, and deer browsing. Note that the prescriptions here include both natural and artificial regeneration, that shelterwood seed cuts may be recommended alone or in combination with either artificial regeneration and deer protection (which could include tree shelters in the case of oaks if ongoing research proves them effective). Note also that a "wait" (wait a few more years for advance seedlings to develop) prescription occurs when the desired level of shading or shelter already exists; this prescription also may be combined with planting and/or protection.

Chart 8.1b is a duplication of 8.1a, except that it deals with stands where interfering plants are expected to cause trouble. Thus, the prescriptions in this chart all include a herbicide recommendation along with the shelterwood, wait, plant, and/or protect recommendations.

Chart 8.1z is to be used in combination with all of the prescriptions obtained earlier, and includes supplementary treatments to be applied along with the primary prescription. These include the need for grapevine control, the need to treat unmerchantable saplings and poles, and the need or desirability of selecting individual stems from the existing stand to be retained after final harvest for specific purposes. If residuals are to be retained, it is important to identify them during any cuts prior to final harvest, so that they are not removed inadvertently at the earlier cut.

Thus, the decision charts provide an outline for the decision process. Major factors such as the adequacy of advance regeneration, expected sprouts, seed source availability, interfering plants, deer browsing, site limitations, and overstory shade conditions are evaluated, and the questions lead you quickly through the decision process.

Some factors of known importance may appear to be missing from the decision charts. For example, we know that acorn insects can be a major factor in oak regeneration. Although not included individually in the decision charts, losses of acorns *are* included in the criteria used to determine whether or not seed supply is adequate. Other pest problems, and many other factors are or could be included in a similar manner, as part of the decision criteria.

Chart 8.1a -- Mature Stand to be Regenerated
Possible Shelterwood Seed Cut

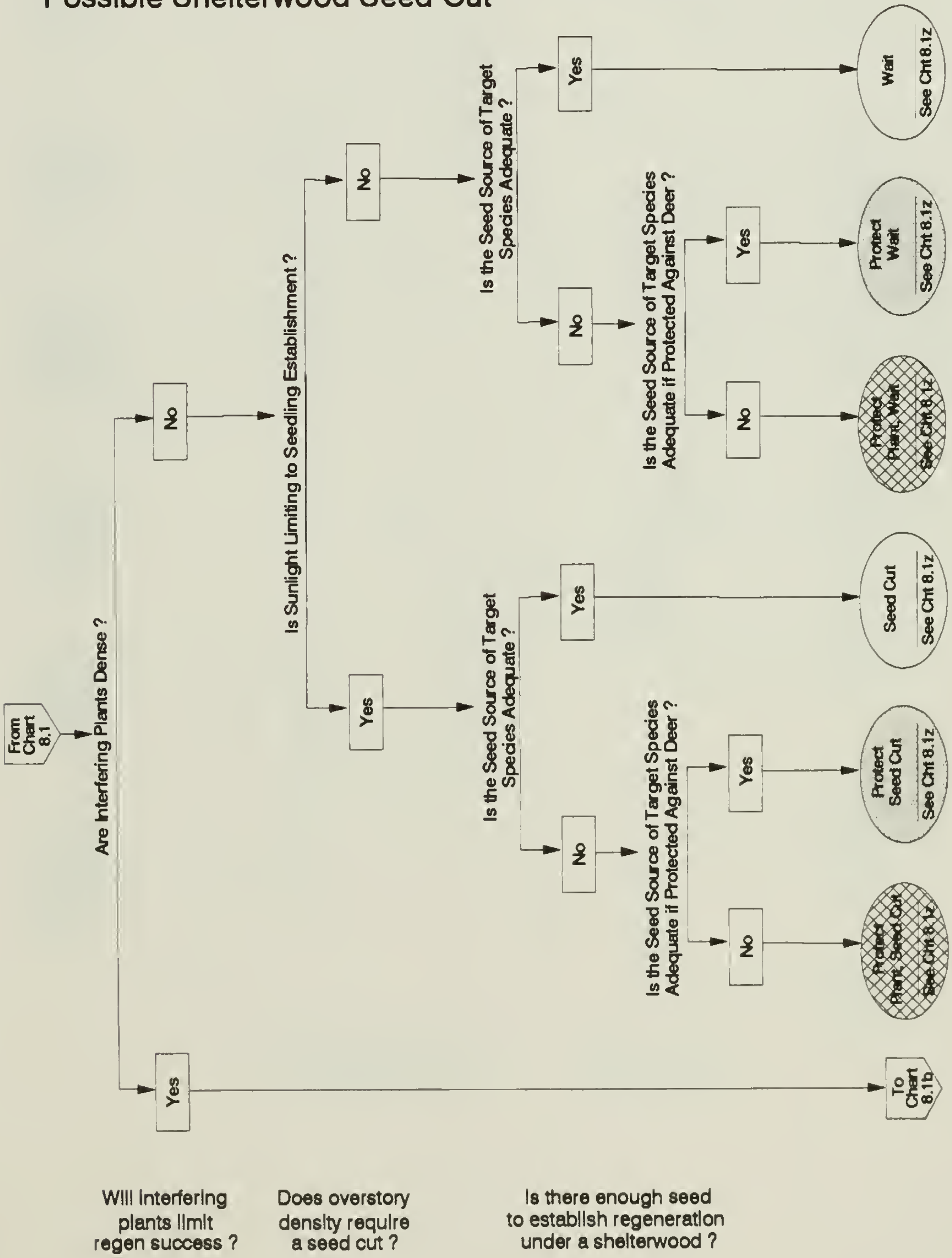
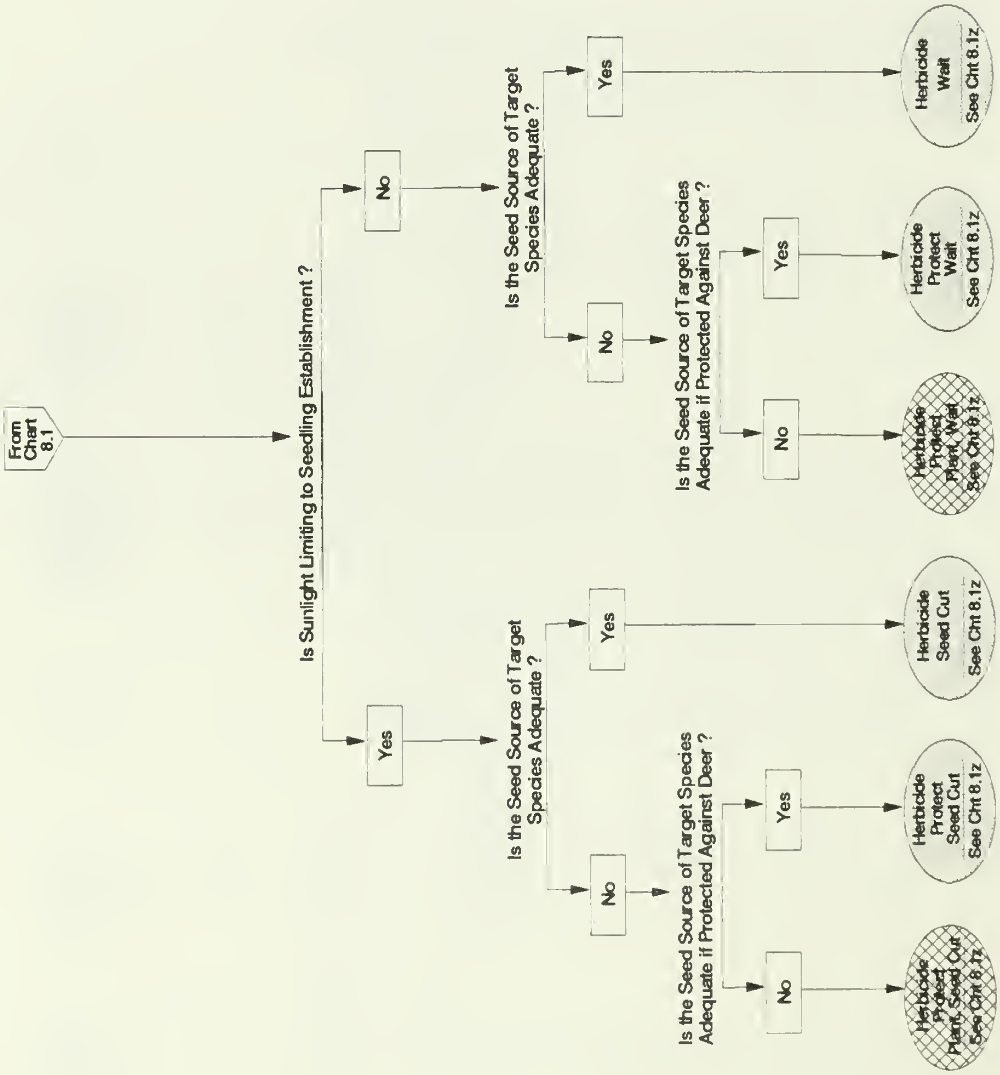


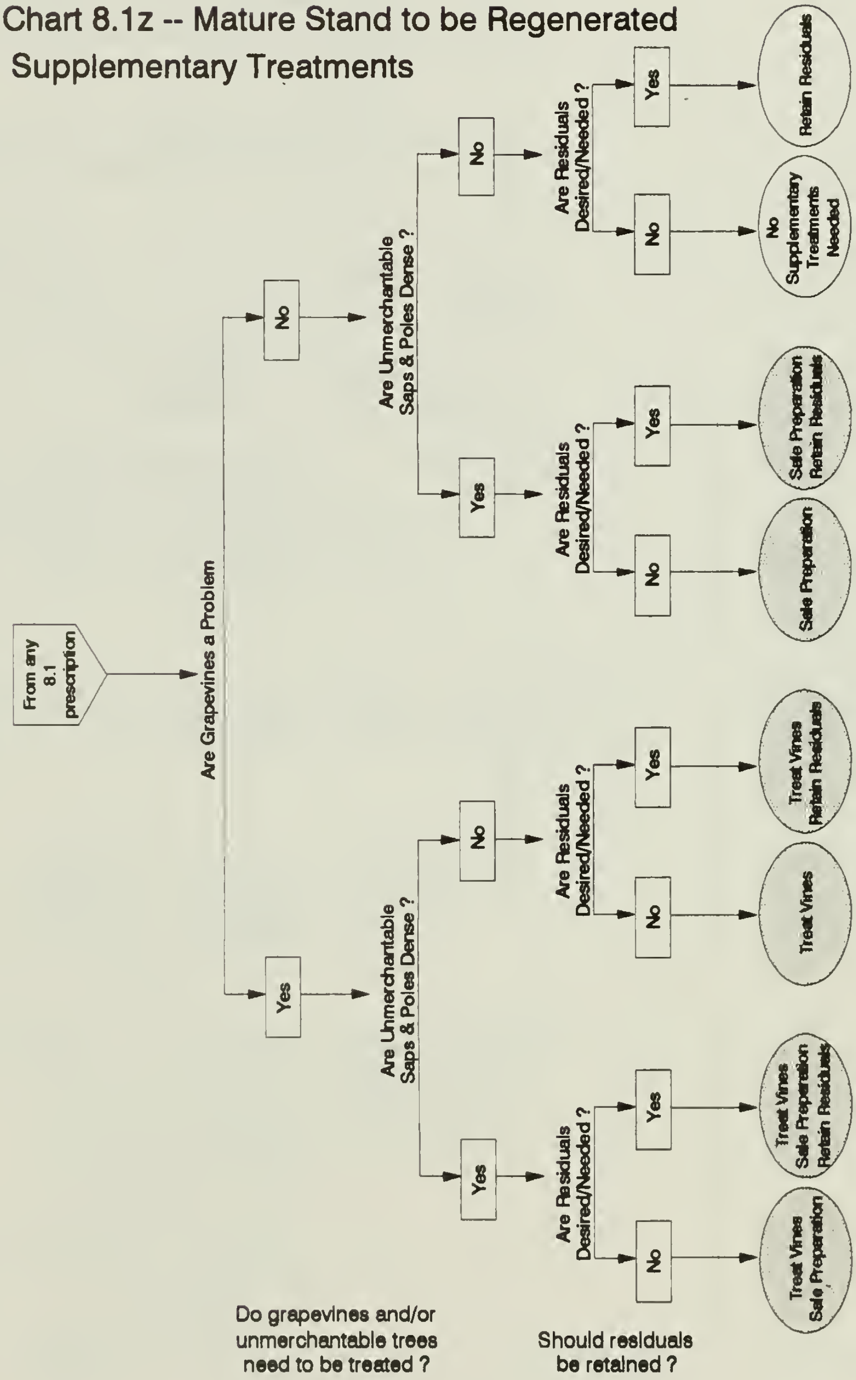
Chart 8.1b -- Mature Stand to be Regenerated Possible Herbicide/Shelterwood Seed Cut



Does overstory
density require
a seed cut ?

Is there enough seed
to establish regeneration
under a shelterwood ?

Chart 8.1z -- Mature Stand to be Regenerated
Supplementary Treatments



Decision Criteria

When using the decision charts, one must answer each decision question either "Yes" or "No." Although the questions and answers appear subjective, it is the intent of the system that these determinations be made as objectively as possible, on the basis of specific parameters that are measured in the stand under question. Tables of these parameters, and the levels that qualify for either a "Yes" or "No" answer, are illustrated in table 1 (from Marquis 1991b). Table 1 is from the Allegheny region. The decision questions are listed in the approximate sequence they are encountered in the decision charts.

Similar tables are being developed for other geographic regions, and for situations where success requires the regeneration of specific target species (such as oaks).

Table 1— Decision criteria for the Allegheny Hardwood Forest Type (from Marquis 1991b)

Decision question	Parameter used to quantify	Decision criteria YES	 NO
Is this stand mature?	MDM (Medial Stand Diameter of the Merchantable trees 5.5+); and AGS RD (Relative Density in Acceptable Growing Stock)	MDM ≥ 18" OR AGS RD <35% (for timber production goal; for other goals, see regulation parameter table)	MDM < 18" AND AGS RD ≥35%
Is this stand in the process of regeneration?	Regen. Stocking: % of plots stocked with two stems over 5 ft. tall	≥70%, but MDM < MDM in regulation parameter table	<70%
Is sapling regeneration adequate?	Sapling Regen. Stocking: % of plots with desirable sapling regen. See Regeneration Stocking Criteria tables in Input Data documentation	≥70%	<70%
Is advance regeneration plus sprouts of target species adequate?	Advance Regen. Stocking: % of plots with minimum number of desirable stems (weighted by height), supplemented by desirable sprouts expected (from overstory data). See Regeneration Stocking Criteria tables in Input Data documentation. Use column for actual deer impact index in this stand.	≥70%	<70%
Is advance regeneration plus sprouts of target species adequate if fenced?	Advance Regen. Stocking: same as above, but using the column for fenced areas (deer impact index = 1) in the table of minimum weighted numbers attached.	≥70%	<70%

Table 1—Decision criteria for the Allegheny Hardwood Forest Type—Continued

Decision question	Parameter used to quantify	Decision criteria YES	NO
Are interfering plants extremely dense?	Interfering Plant Stocking: % of plots stocked with minimum numbers or percent coverage of infering plants. See Regeneration Stocking Criteria tables in Input Data documentation	≥70%	<70%
Are interfering plants dense?	Interfering Plant Stocking: same as above.	≥30%	<30%
Do site factors limit regeneration?	Site Limitations: % of plots on which there is evidence of either poor soil drainage or extremly rocky surface soil	≥30%	<30%
Is sunlight limiting to seedling establishment?	%RD (Relative Stand Density), as the percentage of the maximum basal area expected for stands of this species composition and tree size.	≥75%	<30%
Is the seed source of target species adequate?	Seed Source Index for the target species: calculated from overstory data	Deer Index 1-3 1, 2, or 3 Deer Index 4 1 or 2 Deer Index 5 1	Values other than those under YES
Is the seed source of target species adequate if protected against deer?	Seed Source Index for the target species: calculated from overstory data.	1, 2, or 3	4
Are grapevines a problem?	Grapevine Stocking: % of plots with minimum numbers of grapevines. See Regeneration Stocking Criteria tables in Input Data documentation.	≥30%	<30%
Are unmerchantable saplings and poles dense?	Basal Area/acre in unmerchantable sapling- and pole-sized trees	≥10 sq. ft.	<10 sq. ft.
Are residuals desired or needed?	a) by user choice, in the User Profile, or b) Advance Regen. Stocking plus Residuals Stocking: % of plots stocked with qualifying residuals. See Regeneration Stocking Criteria tables in Input Data documentation	Advance Regen. Stocking ≥50% but <70% and Residuals Stocking plus Advance Regen. Stocking total ≥70%	Any other values

The question "Is sunlight limiting to seedling establishment?" illustrates how specific stand parameters are used to arrive at an objective answer. The stand parameter used to evaluate the density of the overstory and thus the amount of sunlight reaching the forest floor is relative stand density or stocking percent. This measure works well in stands of any species composition, is easily calculated from standard cruise data, and requires no subjective judgment. In stands with more than 75 percent relative density, the overstory is dense enough that sunlight may limit seedling establishment. At lower densities, seedlings can usually become established, although shade-intolerant species may not grow much there. So, 75 percent relative density is the breaking point; at densities above 75, sunlight is considered limiting and shelterwood cutting becomes a possible treatment. At densities below 75, light is probably adequate for establishment and any lack of advance seedlings is probably due to other limiting factors.

Some of the decision questions require much more complex criteria to evaluate adequately. The amount of advance regeneration that is adequate to ensure successful reproduction following harvest is a good example.

In the Allegheny region, adequate advance regeneration requires that at least minimum numbers of seedlings be present over at least 70 percent of the stand area. The minimum numbers of seedlings depends on the species, their size, and the amount of deer browsing expected. Table 2 (from Marquis and others 1992) shows the *weighted* minimum numbers of seedlings required on each plot, as a function of species and deer impact index.

Weighted numbers are derived by counting (or estimating) seedling numbers in each of three size classes, and applying weights to each size class to arrive at a weighted total number. Larger seedlings have a better chance of survival, and thus carry a higher weight than small seedlings.

Table 2—Number of seedlings required for regeneration plots to be stocked, for different levels of deer pressure (from Marquis and others 1992)

	------- Advance regen species group -------				
Deer impact index	**Black cherry**	**Small oak**	**Other desirable species**	**All desirable species**	**Large oak**
	-------- *Weighted number per 6-ft. plot* -------				
5	50	60	200	200	1
4	25	40	100	100	1
3	20	30	50	50	1
2	15	20	30	30	1
1	10	10	15	15	1

The deer impact index is a value determined from a chart showing the estimated deer population (in deer per square mile) for various habitat conditions. Deer population estimates may be obtained from the state game agency, or from a sample census conducted for this purpose. Habitat condition is determined from the proportions of the 1-square-mile area surrounding the stand in question (the deer home range roughly) in such conditions as: agricultural fields, open land, recent harvest cuts, thinned and unthinned forest, etc. All of these vegetative conditions affect the amount of deer food available in the vicinity to reduce browsing pressure on regeneration in any new harvest cuts.

Thus, the evaluation of advance regeneration adequacy is based on the percentage of understory that meets certain required minimum conditions. These conditions vary tremendously depending on such factors as tree species, seedling size, and deer pressure. To illustrate: in the Allegheny region, the minimum number of maple or ash seedlings per 6-ft. radius plot is 100, if deer pressure is high (level 4) and all seedlings are 2 in. to 1 ft. tall; but, the minimum number is only 7 or 8 if deer pressure is low and all seedlings exceed 1 ft. in height.

Since the decision question in the chart considers both advance regeneration and sprouts, the sprouting potential of all trees to be cut must also be evaluated. Then, estimates of the proportion of the area that will be regenerated by sprouts must be added to the advance regeneration estimates.

Thus, a simple "Yes" or "No" answer in this case involves a whole host of factors that must be carefully evaluated to make effective use of the decision charts. Other decision criteria, such as the density of interfering plants and seed supply adequacy, are evaluated in a similar manner. Several factors must be included in determining whether or not these factors are limiting to or are adequate for regeneration. Details on these and other factors for the Allegheny region are presented in the SILVAH literature (Marquis and others 1992), and are not repeated here.

Developing suitable decision criteria for a specific forest type and geographic region is a major task. In the Allegheny region, it took nearly 15 years of research aimed specifically at that goal to complete the SILVAH system. Information needed to develop decision criteria for other regions and forest types that have received less focused research effort will not always be available.

Nevertheless, many of the general principles and procedures from the Allegheny region can be used elsewhere, and experienced silviculturists can probably make informed estimates of the critical parameters in their areas. Such estimates provide a starting point that is certainly better than no system at all. At the very least, it forces the decision-maker to systematically consider all of the many factors that affect regeneration success, and to make a judgment on each based upon the best information currently available.

Furthermore, the system itself serves as a model or framework on which to evaluate research needs. Those factors or criteria on which knowledge is inadequate become quickly apparent as one attempts to define the decision questions and criteria. The relative importance of each research need also can be assessed in terms of its relative importance and frequency of occurrence in the overall oak regeneration process.

The decision charts presented here are intended for general use over a wide range of forest types and geographic areas. As a result, some of the decision points and decision criteria will be of little importance in some types or regions. Rather than creating a whole series of specialized charts that eliminate these factors entirely for the charts for that region, it is best to simply set the criteria at a level that will effectively ignore the factor. For example, deer browsing may not be a factor at all where deer populations are low across a wide geographic area. In these cases, the criteria table can simply suggest that deer impact index be set to 1 (very low) or 2 (low) anywhere in that region.

Additional decision criteria are being formulated to extend this system of decision making to a wide variety of resource values. For example, visual qualities within a forest stand are highly dependent on numbers and sizes of woody stems close to the ground, as is habitat quality for many wildlife species. Criteria that ensure the desired stems densities for these objectives fit very comfortably in this system.

Data Requirements

To function consistently, any stand analysis and prescription system must have reliable data on which to answer the decision questions. In SILVAH and the NE Decision Model, that data come from a cruise in the stand under consideration. Data on overstory and understory vegetation and site factors are collected and summarized for use in the decision charts. Computer programs ease the calculation job and permit extensive analyses to be performed as needed.

The amount of detail collected in the cruise can be varied to meet the needs of a variety of organizations and individuals, although there are certain essential data items that must be collected in all cases. The recommended cruise procedure involves:

1. A variable-radius (prism) cruise of the overstory, recording trees by species and diameter at the minimum, with other observations on individual trees as desired (such as merchantable height, timber quality, grade, defect, wildlife value, etc.).

2. A fixed-plot sample of understory conditions, with several options in the amount of detail recorded. At the minimum, a simple checkmark is used to indicate the presence or absence of 15 to 20 specified conditions (such as the presence of various categories of advance seedlings and interfering plants). Estimated numbers or percent of coverage may also be recorded for each of these classes. Or, complete enumerations may be made of all vegetation by species and size classes.

3. A fixed-plot sample of site conditions. At the minimum, this involves a checkmark to indicate the presence of certain site factors known to limit regeneration. It may also include site index or site class determination and recording of other important site factors.

Because understory and site conditions vary considerably within a stand where overstory conditions are uniform, we recommend that twice as many understory plots be sampled as overstory plots. Understory and site data can easily be collected at the same time as overstory data. Understory and site plots are taken at each overstory plot, and additional understory/site plots are located half way between each overstory plot.

When the SILVAH system was first introduced, there was some reluctance on the part of forest managers to collect understory and site data. Traditional cruises included only the overstory (often only the merchantable size trees), and it was assumed that the extra data collection would add considerably to cruise costs. However, studies by both the Allegheny National Forest and Hammermill Paper Co. revealed that collecting the minimum understory and site data did not add much to the time required. Recording simple checkmarks at each understory plot took only a few minutes per plot, and was insignificant compared to the time required to lay out cruise lines, walk from plot to plot, and collect prism data.

Of course, more detailed understory data collection would add significantly to cruise time and costs. Although the minimum data collection provides sufficient information for prescription preparation, extra data may be desirable for a wide variety of reasons. Each organization must tailor data collection to its own needs and budget. The system is designed in such a way that it can utilize the added data if available, but can still function for writing prescriptions with the minimum data.

SUMMARY

Failure to obtain prompt regeneration of desired species after a harvest cut can leave a stand unproductive for many decades, cost excessive amounts to reclaim through artificial means, and severely limit the suitability of the stand for a wide range of forest values. But prescribing silvicultural treatments that ensure successful regeneration most of the time is a difficult task.

Forest managers need to consider all the many factors that could affect regeneration success, weigh the many available silvicultural techniques available to accomplish the task, consider the characteristics of the particular stand under consideration, and make an informed decision that is most likely to achieve the desired conditions. The decision-making procedures described here provide a systematic way to analyze stand potential and prescribe regeneration treatments. In the Allegheny region where the system has been used extensively, successful regeneration has been obtained in over 90 percent of the stands harvested, compared to only about 50 percent prior to development of this system. The procedures can be adapted for use in any geographic region or forest type.

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Natural Regeneration of Oaks

Regenerating Oaks in the Central States

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ABSTRACT

Although oaks are the most abundant overstory species in many upland stands in the Central States, they are often replaced in the reproduction that follows harvesting of current oak stands because of the lack of adequate oak advance reproduction. Obtaining adequate oak regeneration is especially difficult on highly productive sites where understories are often well developed and dominated by shade-tolerant species. Recommended regeneration methods for these upland stands are based on an evaluation of the oak regeneration potential. Where the regeneration potential is low because oak reproduction is absent, sparse, or too small, stand treatments to enhance oak reproduction establishment and growth are described. Silvicultural treatments for individual stands will vary with site quality, competing species (especially fast-growing competitors such as yellow-poplar) and physiographic-ecological region.

INTRODUCTION

In the Central United States, geologic history, physiography, and climate vary greatly and many different associations of soils, water, plants, and animals are present. Braun (1950) described the forest regions of Eastern North America using remnants of the "presettlement" forests. The Central United States includes parts of her Oak-Hickory, Western Mesophytic, Mixed Mesophytic, Oak-Pine, Oak-Chestnut, Beech-Maple, and Maple-Basswood forest regions (figure 1), each with its own distinctive characteristics but with wide variation of forest vegetation. Oaks have always been an important stand component in these regions and currently dominate most of the mature or nearly mature stands. Even so, the oak component of new stands following harvesting of many mature stands is often less than expected or desired.

It is generally accepted that a key to replacing these stands with new oak stands is having well-established oak advance reproduction in place when the final harvest is made. Sprouts from stumps of cut overstory trees are also important. It is now apparent that existing oak advance reproduction plus stump sprout potential is not adequate to replace many current oak stands, especially those on the most productive sites. How then do we ensure that when the stand is ready to harvest the oak advance reproduction will be adequate to replace it?

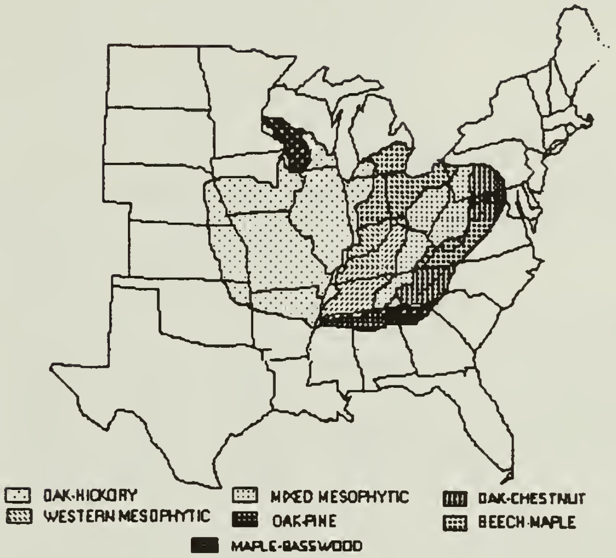

Figure 1—Area of central hardwoods with Braun's Forest Regions.

EVALUATING OAK REGENERATION POTENTIAL

When planning regeneration harvest cuts in oak stands, the important first step is to evaluate the potential of the oak advance reproduction plus stump sprouts to replace the current stand. Oak advance reproduction differs greatly in number and size of individuals. Some of this difference can be attributed to site quality; in general, oak advance reproduction in the Central States is more abundant on average to poor sites than on good sites (table 1). Size of individual stems is important because growth after final harvest is related to both stem height and basal diameter. Thus, height and basal diameter are indicators of total plant size and the potential of the root systems to support vigorous growth after overstory removal.

Assessing oak regeneration potential involves making an inventory of advance reproduction and trees over 2 in. d.b.h. in the midstory and overstory. The advance reproduction data are used to determine the probability that a stem of a given size will attain a specified height by the time it is 5 years old. These probabilities are then adjusted to account for drop-out from mortality and suppression to age 20. Probabilities have been developed for the Ozark Forests in Missouri and are related not only to stem size, but also to aspect and slope position. For stems of equal height and basal diameter, the probabilities are highest on southeast- and northwest-facing middle slopes and lowest on lower, northeast slopes (Sander and others 1984). The coefficients in the regeneration potential equation apply specifically to Missouri and must be used cautiously in other areas.

The midstory and overstory inventory data are used to estimate the proportion of stump sprouts from cut trees that can reasonably be expected to produce dominant or codominant oaks at age 20. This estimate, together with the advance reproduction probabilities, is used to determine if the new stand can be expected to develop into a predominantly oak stand by age 20.

This evaluation procedure is for oaks only. The new stand will contain other species, but we do not have a procedure to estimate their contribution to future stand stocking. We can get a general idea of what the new stand composition might be by looking at the total composition of the advance reproduction and the composition of the overstory (table 1).

Table 1—Advance reproduction per acre on good and average sites in some Central States

State	Oaks[1]	Hickory	Maples	Yellow poplar	White Ash	Other Trees[2]	Total Trees	Under-Story[3]	Total Stems
					Good Site				
Arkansas	940	820	1420	–	430	1640	–	4420	–
Indiana	500	360	4350	40	1570	1000	7820	3570	11390
Kentucky	1460	610	1840	150	0	690	4750	2920	7670
Missouri	1430	640	380	–	0	420	–	2060	–
Ohio	1960	550	860	240	80	390	4080	3770	7850
					Average Site				
Arkansas	1950	600	1960	–	460	1560	–	3370	–
Indiana	1580	100	1640	50	800	400	4570	5330	9900
Kentucky	1070	580	870	140	490	630	3780	1510	5290
Missouri	1510	514	329	–	0	440	–	1540	–
Ohio	3640	700	420	140	0	840	5740	7310	13050

[1] White, black, northern red; includes scarlet oak in Missouri and scarlet and chestnut oaks in Indiana, Kentucky and Ohio.

[2] Good Sites: Elm, blackgum, scattered black cherry and black walnut. Includes American beech in all states except Missouri. Also includes sweetgum in Arkansas. Average Sites: Primarily blackgum in all states.

[3] Good Sites: Primarily flowering dogwood, redbud, hazelnut, witch-hazel, paw-paw, and hophornbean. Includes sourwood in Kentucky and Ohio. Includes Carolina buckthorn in Arkansas. Average Sites: Primarily flowering dogwood, sassafras, and serviceberry. Includes sourwood in Kentucky and Ohio, Carolina buckthorn in Arkansas, and hawthorn in Missouri.

When yellow-poplar is an overstory component, its regeneration potential will be substantial. This potential exists because numerous yellow-poplar seedlings will appear, even after partial harvests, from the large quantity of viable seed in the litter and humus. The primary source of reproduction of species such as white ash, black cherry, hickories, maples, elm, blackgum, dogwood, sourwood, and sassafras is advance reproduction. Like the oaks, their growth after harvest is related to their pre-harvest size; relatively large advance reproduction stems have a higher potential for competing successfully than small ones. Stump sprouts are also an important source of regeneration for these species. Although we do not yet have a system for estimating success probabilities for species other than oaks, we can expect at least some of them to become a dominant component of the reproduction stand after harvest if they are present as relatively large advance reproduction.

CHOOSING A REGENERATION METHOD

The choice of which regeneration method to use must be based on the outcome of the regeneration potential analysis, the basic ecology of the forest region in which the stand is located, and the overall management objective. On many sites in the areas east of the Mississippi River it is not realistic to expect to be able to naturally regenerate essentially pure oak stands even though the current stand is dominated by oak. The ecological trends due to effective wildfire control, and results of past regeneration efforts, indicate many future stands will be mixtures of a number of species especially on high-quality sites. An oak component can be retained readily on average sites, but on good sites the stands will most likely be dominated by species other than oaks.

If the oak reproduction potential is adequate to replace the current stand, clearcutting is the best method to use. Although understory species may appear to dominate the stand for about 10 years following clearcutting, the oaks and other overstory species begin to assert dominance, and by age 10-15 the understory species are generally in a subdominant position.

If oak reproduction potential is not adequate and the stand is clearcut, the new stand will be dominated by a varying mixture of species. With the exception of yellow-poplar, the species that dominate the advance reproduction will be predominant in the new stand. Yellow-poplar will also be abundant if it is present in the overstory, and some oaks will probably be present.

When oak advance reproduction is small, scarce, or absent, the regeneration method most likely to produce the best results is the shelterwood method. However, the method must be tailored to produce the micro-environments required by oaks for successful seedling establishment and early seedling growth. These micro-environments are still largely unknown and are likely to differ among differing ecological regions. For example, because of the differences in the basic ecology between the Mixed Mesophytic and the Oak-Hickory forest regions, what is required in one of these areas may not be required in the other.

In 1979, a study of the shelterwood method with overstory densities of 40, 50, and 60 percent stocking and three understory treatments that ranged from heavy (all non-oaks treated with herbicide) to none, was started in Missouri's Ozarks. At the time of treatment the number of oaks per acre varied from about 300 to 1,100 per acre on good sites (Black oak site index 75+) and from about 600 to 1,200 per acre on average sites (Black oak site index 60-75) (Sander 1987). However, a large majority of them were less than 1 ft. tall, much too small to compete if the stands were clearcut. Ten years after treatment the total number of oaks increased and ranged from about 600 to 1,800 and about 2,500 to 3,500 per acre on good and average sites respectively (figure 2), although the total number of oaks increased in all treatments at all overstory stocking levels.[1] Even so, when the advance reproduction evaluation criteria were applied to these plots, stocking values were less than one-half that required for successful oak regeneration on the good sites. Furthermore, about 50 percent of the large reproduction is understory species, primarily dogwood and sassafras. Maple, hickory, and blackgum account for an additional 15 to 25 percent of the large reproduction. Thus the oaks, particularly the smaller stems, are still at a competitive disadvantage.

On the average sites understory treatment had little effect on increasing the number of large oaks, but there were more large oaks on the 40 percent stocking plots than on the plots with higher stocking[1]. The advance reproduction stocking values are

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[1] Schlesinger, R.C., Sander, I.L., and Davidson, K.R. 1992. Unpublished draft on file: North Central Forest Experiment Station, Columbia, MO.

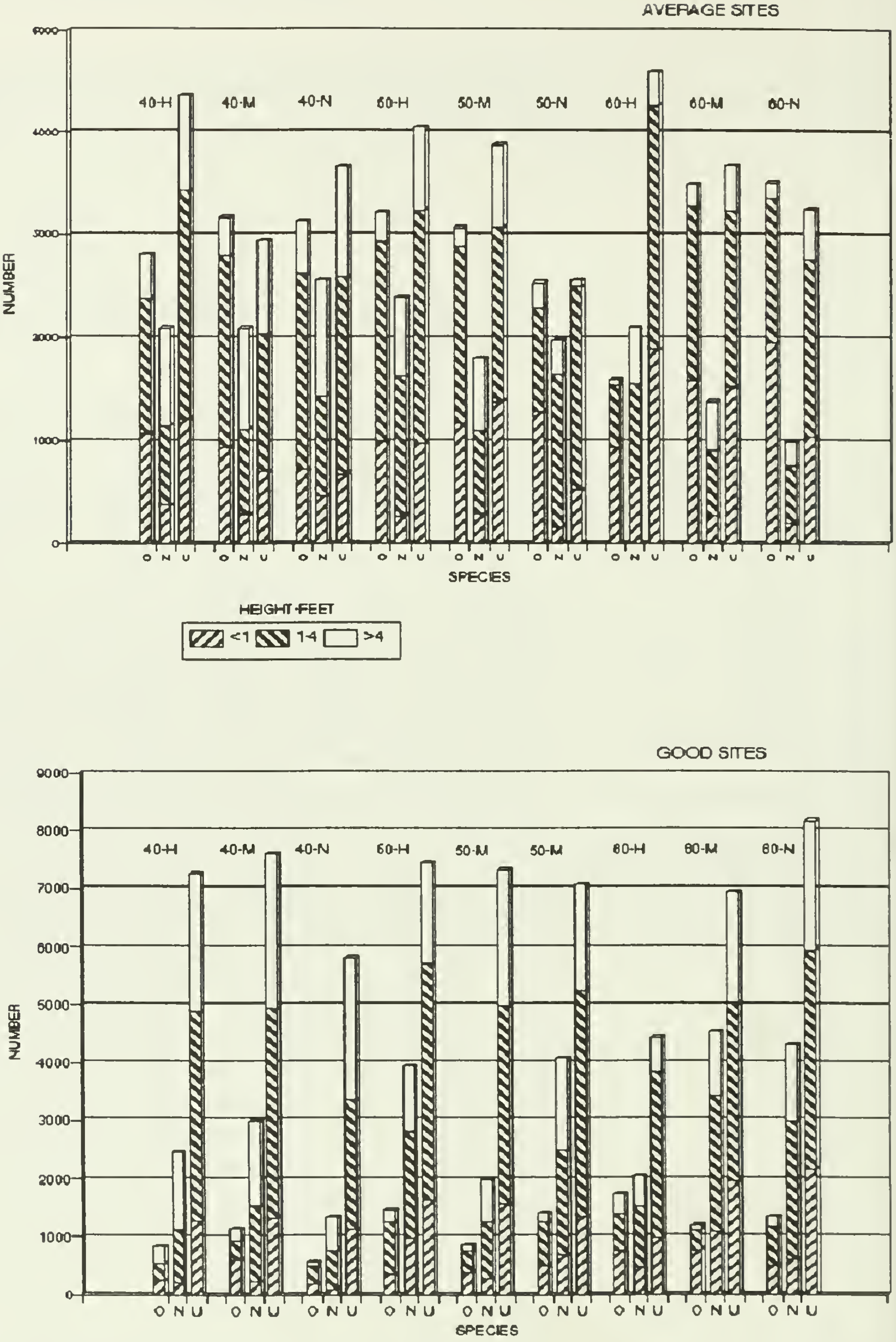

Figure 2—Reproduction per acre 10 years after shelterwood cutting in the Missouri Ozarks. Species: O—oaks, N—non-oak overstory species, U—Understory species. Treatments: Overstory—40-, 50-, and 60-percent stocking; Understory—H, Kill all non-oaks; M, Kill all non-oaks taller than 6 ft.; N, Kill nothing.

now close to those required for successful stand regeneration on the 40 percent stocking, but only about one-half to two-thirds of the required value on the higher density plots. The large reproduction is still dominated by hickory, black gum, sassafras, and dogwood. However, the large oaks appear to be at least holding their own and should in a few more years be adequate to replace the original stands.

Results from a similar study in southern Indiana show that all treatments failed to increase the number of oaks. There were few oaks present before treatment so a major objective was to get new oaks established. Two things occurred that precluded new oak seedling establishment. One was the lack of any acorn production the first 3 years after treatment, and the other was the very rapid regrowth of the understory. Nine years after treatment a major windstorm damaged nearly all of the plots and the study had to be abandoned. Although these early results are somewhat discouraging, they provide valuable information and insight for future research, and are useful for making immediate recommendations for using shelterwood cutting to regenerate oaks.

Interest in uneven-age regeneration methods, particularly the group selection system, has increased greatly in recent years. This interest has come about because of political and sociological pressures against clearcutting. Research on the effect of opening size on regeneration has demonstrated that oaks can be reproduced in small openings as well as in large ones (Minckler and Woerheide 1965, Sander and Clark 1971, Smith 1981). However, the requirements that apply to clearcutting also apply to group selection. Creating an opening, even a small one of one or two tree heights in diameter, will not in itself ensure oak reproduction. Oak advance reproduction of adequate size and in adequate numbers must be present where openings are created in order to achieve successful oak stand replacement.

We cannot, however, consider only the regeneration when we use group selection. Because it is a variation of the single-tree selection system, we must also strive to achieve and maintain a reasonably well-balanced diameter distribution. We have only begun to address the problem of how the reproduction in groups eventually contributes to overall future stand structure, and how to maintain balanced diameter distributions in oak stands has not been determined.

REGENERATION GUIDELINES

The first step in planning for oak regeneration is to evaluate its regeneration potential. The results of this evaluation will determine which even-aged regeneration method should be used. Or, if group selection is planned, such an evaluation can help determine where to locate groups and can provide information on which species are reproducing and how the reproduction is growing.

Even-Age Methods

Clearcutting. If the oak advance reproduction plus stump sprouting is adequate, clearcut.

When clearcutting:

1. Determine size of area to be designated as a stand. Stand size can vary but should be at least 2 acres. Stands smaller than this have a large proportion of their area in a zone around the stand border where reproduction growth will be slow

because of the influence of the surrounding trees. A stand should preferably be restricted to a single condition or size class of timber and site quality. Size of the forest property will also influence stand size. In areas where deer populations are high, stand size may need to be relatively large in order to reduce the impact of browsing on reproduction growth.

2. Arrange and shape clearcuts so they mingle with uncut stands and blend into the landscape as much as possible.
3. Plan, construct, and maintain skid trails and logging roads to minimize erosion.
4. Harvest all merchantable trees.
5. Cut or kill remaining culls and small trees larger than about 2 in. d.b.h. Killing the unwanted trees instead of cutting them reduces sprouting and provides snags for nesting holes and perches for birds. Cutting some of them will provide habitat for other wildlife species such as ruffed grouse.
6. There may be some other options for harvesting and getting rid of the unwanted and unmerchantable trees. These options are generally used for special purposes, such as to soften the aesthetic impact or provide special wildlife habitat. Their use depends on owner policy rather than silvicultural desirability.

If the clearcut stand is on southeast or northwest middle and upper slopes, we can expect to have a stand at about age 20 that can be molded into an essentially pure oak stand by thinning. On north and east aspects and lower slopes, the stand composition may be highly variable. In the mixed and western mesophytic forest regions, yellow-poplar will likely be abundant. Other species such as white ash, black cherry, and red and sugar maples will also be present. However, if the oak advance regeneration is adequate, we can expect to have a predominantly oak stand 20 years after clearcutting.

Shelterwood. When the regeneration potential of the existing oak advance reproduction is not adequate to replace the stand, use the shelterwood method. Oak advance reproduction is most likely to be inadequate on the middle and lower north- and east-facing slopes, where it will be difficult to obtain oak regeneration. Costs will be high because of the intensive site preparation needed on these high-quality sites.

When applying the shelterwood method:

1. Determine stand size, arrangement, and shape the same as for clearcutting.
2. Control the understory by cutting or preferably killing the non-oak species that will compete with the small oaks in the oak-hickory and oak-pine forest regions.
3. Reduce the overstory to 40-60 percent stocking. In the other forest regions, a somewhat higher stocked residual stand (70-80 percent stocking) might be desirable to inhibit yellow-poplar seed germination and rapid redevelopment of the understory. Leave the best dominant and codominant oaks as uniformly spaced as possible. Kill all stems of unwanted species.
4. If possible, apply the understory and overstory treatments before seedfall in a good seed year.
5. Monitor seedling establishment and growth and make additional light cuts to keep the overstory from restricting growth. Apply additional understory control if the understory redevelops to a point where it restricts the oak reproduction

growth. This control may be desirable 5-10 years after the original treatment, particularly on high-quality sites.

6. When the regeneration potential of the oak reproduction is adequate to replace the stand, remove the remaining overstory trees in one cut.

The length of time required to establish oaks and grow them to adequate size under a shelterwood is not yet known, but will probably be 10 to 20 years or more.

Uneven-Age Methods

Single-tree selection. The establishment and development of oak regeneration is not possible using the single-tree selection system. Harvesting single trees to achieve and maintain a specific diameter distribution does not provide the microclimate needed for oak regeneration, but does provide the conditions needed for the establishment and growth of shade-tolerant species. Over time, single-tree selection will convert the stand from oaks to shade-tolerant species.

Group selection. This method can be used to reproduce oaks satisfactorily, but the diameter of the circular openings created should not exceed 1 to 2 times the height of the surrounding dominant trees in order to maintain the uneven-age character of the stand.

When applying group selection cutting:

1. Evaluate the potential of the oak advance reproduction to fill each opening (group) that will be created by cutting.
2. If the oak advance reproduction is adequate, harvest the merchantable trees in the group and cut or kill remaining culls and small trees as described under clearcutting. The reproduction response will be similar to the responses after clearcutting except that reproduction growth will be retarded in a large part of the opening area because of the influence of the surrounding stand.
3. If the oak advance reproduction is not adequate to fill the opening, cutting the trees to create the opening will not result in oak reproduction and the opening will be filled by whatever species are present in the understory. In this case, follow the procedure for the shelterwood method where the openings will be located. The percentage stocking goal may not be attainable in the small groups, so make sure seed-producing oaks are left where the groups will be located. Treat the understory as in the shelterwood system. Removing sub-canopy overstory trees and the understory competition may be all that is needed to increase the amount of light reaching the forest floor and enhance oak reproduction establishment and growth.
4. Cut trees also between the groups to maintain the selected diameter distribution and to enhance oak reproduction establishment and growth throughout the stand.
5. Group selection may not be successful in areas with high deer populations because of excessive browsing in the small openings.

IN CONCLUSION

There is no guarantee that applying the above guidelines will regenerate oaks successfully in all situations. However, doing nothing in the current mature or nearly mature stands will not increase the chances of regenerating oaks. On high-quality sites in particular, regenerating oaks is a difficult task. In some parts of the Central States, particularly in the mixed and western mesophytic, Maple-Basswood, and Beech-Maple forest regions, regenerating essentially pure oak stands on high-quality sites may not be possible. However, oaks have always been components of stands in these forest regions on all sites and it is likely that oaks will at least be a component in future stands. In the Oak-Hickory and Oak-Pine forest regions, oak regeneration should not be difficult to obtain on average sites; however, on high-quality sites intensive treatments are probably going to be necessary.

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Regenerating Oaks in the Bottomlands

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ABSTRACT

Bottomland oaks depend on advance reproduction and stump sprout potential for successful natural regeneration. Large seedlings must be present or be developed prior to harvest to ensure successful regeneration of oaks. Small oak seedlings, with their slow initial growth rates, are not able to compete with the faster initial growth of other species. This paper addresses the effects of the various methods of reproduction on the regeneration of bottomland oaks.

INTRODUCTION

Bottomland forests are some of the most productive and diverse ecosystems in the United States, yet they are poorly understood. Hardwood regeneration in the bottomlands can be established by most reproduction methods. Problems occur when foresters want to regenerate stands to specific species, particularly oaks. A myriad of different species with different site requirements and growth habits makes regeneration of oaks extremely complex and variable.

Although regenerating bottomland oaks is a major concern in these forests, Hodges (1989) stated that

> "the answer to the question of how to ensure adequate oak regeneration in bottomland hardwood stands is not the development of some radically new method of cutting, but recognition that all cutting operations in the stand, from the very first, should have as some of their objectives creation of an environment, largely light conditions, favorable for oak regeneration" . . . and furthermore . . . "ensure that cuttings occur frequently enough to maintain growth of oak regeneration."

Unfortunately, most bottomland stands in the South are not managed. Stand structure typically ranges from closed canopies with little advance reproduction to cutover, mismanaged areas where species composition and tree quality are poor. Regeneration of such stands is certainly complex, variable, and difficult to predict.

This paper discusses various species-site relationships and reproductive mechanisms that should be considered when regenerating bottomland oaks and the various methods of reproduction that can be used to obtain successful oak regeneration. The term "bottomland oaks" in this paper refers to: cherrybark oak, Nuttall oak, Shumard oak, swamp chestnut (cow) oak, water oak, and willow oak. Maps showing the distribution of these bottomland oaks can be found in Burns and Honkala (1990).

SPECIES-SITE RELATIONSHIPS

When natural regeneration methods are used to perpetuate bottomland oaks, the first step should be a detailed evaluation of site and stand conditions to determine the potential for regeneration (Johnson and Deen, in press). Matching appropriate species to suitable sites is especially important considering the wide variety of landforms (bars, levees, ridges, flats, sloughs, terraces) found in bottomlands and the different species of oak, each with specific silvical characteristics and site requirements (McKnight and others 1981). Slight, nearly undetectable elevational changes in bottomlands alter species-site suitabilities (Hodges and Switzer 1979). Other factors affecting regeneration are the frequency, depth, timing, and duration of flooding and the species' tolerance to flooding. Baker and Broadfoot (1979) published a site evaluation guide for commercially important bottomland hardwoods. Typical species compositions for particular landforms have been developed for the major bottoms of the lower Mississippi alluvial plain and the minor bottoms of the Gulf coastal plain (figure 1) (Hodges and Switzer 1979) and the red river and black river bottoms of the Atlantic coastal plain (Kellison and others 1988).

Along with flood tolerance, shade tolerance is another variable in the regeneration equation. Bottomland oaks range from intolerant to intermediate in their tolerance of shaded conditions (Putnam and others 1960) and most require some direct overhead sunlight to survive and grow (Johnson 1979). Even though oak seedlings will become established in almost any size of opening, continued growth and development require large openings. In small openings, sunlight becomes a limiting factor, especially as canopies close, and actually favors the more tolerant species. Consequently, bottomland oaks are managed most successfully by implementing an even-aged silvicultural system (Kellison and others 1988).

REPRODUCTIVE MECHANISMS

When planning for natural regeneration of bottomland oaks, the presence of advance reproduction in both size and number is essential for success (Hodges and Janzen 1987). Oak regeneration consists of three forms of reproduction:

(1) New seedlings from seed in place.

(2) Seedlings that developed over a period of years prior to harvest (i.e., advance reproduction).

(3) Seedling and stump sprouts.

New oak seedlings generally cannot compete with sprouts and previously established reproduction (Johnson and Krinard 1976). Sprouts of oak trees less than 10 in. in diameter are a dependable source of regeneration because of their well-established root systems and vigorous growth potentials (Janzen and Hodges 1987). However, stems greater than 10 in. in diameter exhibit a markedly reduced sprouting potential. Consequently, in stands composed primarily of large trees, stump sprouts are not a reliable source of regeneration, so that a build-up of advance reproduction in size and number over a period of years appears to be necessary before final harvest (Johnson 1979, Loftis 1990). These larger seedlings compete more successfully with other vegetation when the overstory is removed and show good sprouting potential if severed (Janzen and Hodges 1987).

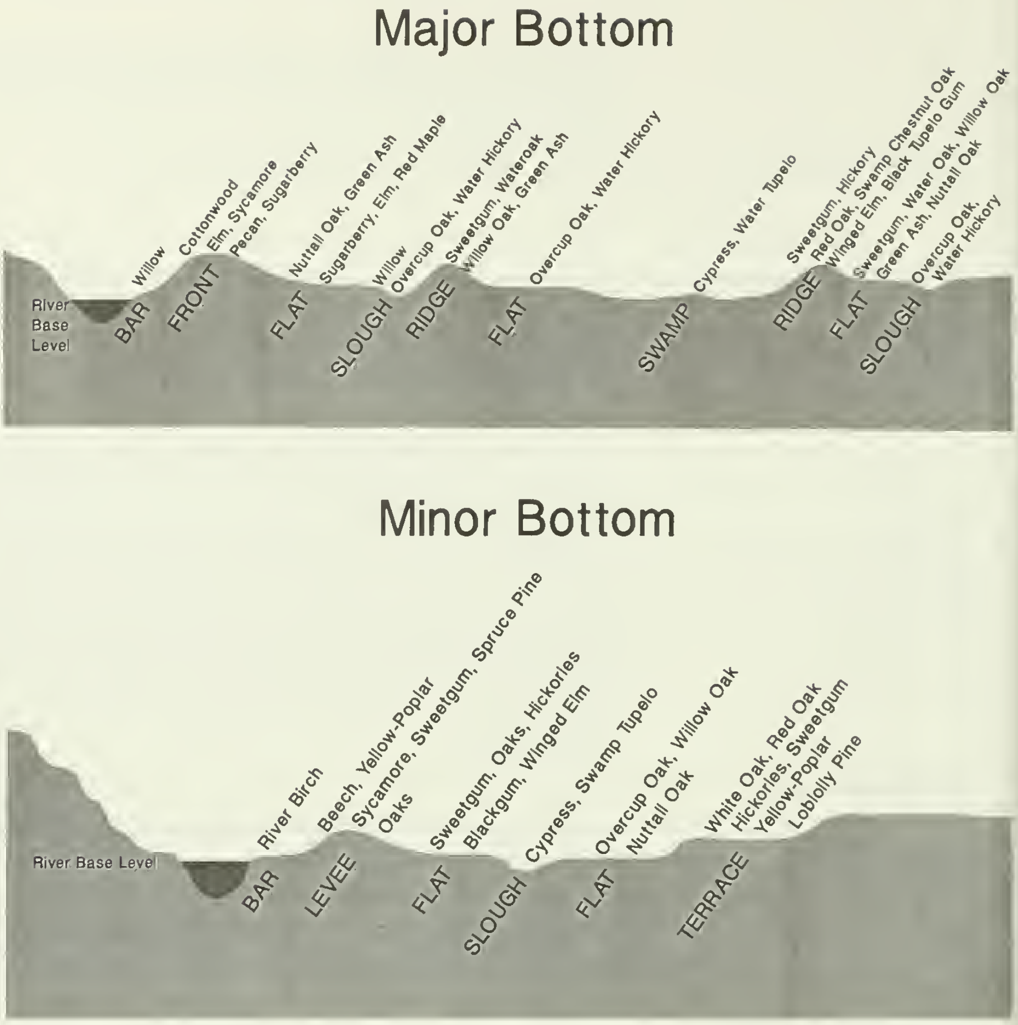

Figure 1—Cross-section of a major and minor stream valley showing relationship of relief features and typical species association (Hodges and Switzer 1979).

A key to establishing and developing advance reproduction for natural regeneration is in the regulation of light reaching the forest floor (Hodges 1989). Too much or too little light can have detrimental effects on regeneration efforts. Full sunlight may promote faster-growing species rather than oak, while limited light will benefit more shade-tolerant species. In the absence of fire and grazing, most bottomland stands have dense midstories and understories of tolerant species which hinder the regeneration of oak. Research and experience indicate that failure to treat this undesirable and unmerchantable component causes reduced stocking and growth of oak regeneration (Deen and others, in press).

Johnson and Deen (in press) developed a numerical rating system to evaluate the potential for successful regeneration of southern bottomland hardwood stands. The system is based on the number and size of advance reproduction as well as on stump and seedling sprout potential. If regeneration potential is adequate, the stand can be harvested. If not, additional sources of regeneration must be secured naturally by manipulation of the overstory and/or lower canopies to allow development of advance reproduction, or by artificial means, such as direct-seeding or planting. Similar evaluations of regeneration potential have been developed for the Northeast (Marquis and Bjorkham 1982) and the Midwest (Sander and others 1976).

Tables that show the occurrence, shade tolerance, flood tolerance, and reproductive characteristics of many bottomland species including oaks have been synthesized from the literature by McKnight and others (1981). The bottomland oak components of these tables are shown in table 1. An understanding of these species-site relationships and reproductive strategies is helpful when making decisions on oak regeneration and management.

Table 1—Occurrence, shade and flood tolerance, and reproductive characteristics of the bottomland oak species[1]

Common and scientific name	Occurrence in bottomlands	Shade tolerance	Flood tolerance	Reproductive characteristics
Cherrybark oak (*Quercus falcata* var. *pagodifolia* Ell.)	Widely on best loamy sites on all river bottom ridges and better drained creek bottoms and hummocks. Mostly on older alluvium. Occasionally on tight, silty clay, but grows poorly there.	Moderately intolerant to intolerant.	Weakly tolerant to intolerant. Seedlings can withstand very little flooding. Viability of acorns greatly reduced by submersion.	Seed dispersed Sept.-Dec. by gravity, birds, and animals—seldom by water. Seedlings may start in shade, but cannot survive long. Not a good stump sprouter.
Nuttall oak (*Q. nuttallii* Palmer)	Widely on flats, low ridges, shallow sloughs, and near margin of swamps, in recent alluvial sites. On older alluvium mainly restricted to wet, heavy but not impervious sites. Restricted to major streams entering the Gulf and their large tributaries.	Intolerant.	Moderately tolerant. Seedlings killed by high water during growing season. Viability of acorns not reduced by 34 days of submergence.	Starts readily in either shade or openings but soon dies in shade. Persists against all ground cover except heavy peppervine. Many large trees are of sprout origin.
Shumard oak (*Q. shumardii* Buckl.)	Mainly on terraces in older alluvium and outwash from upland and well drained creek bottoms and hummocks. Rare on newer soils. Widely distributed but scattered.	Intolerant.	Weakly tolerant. Seedlings relatively intolerant to flooding.	Seed dispersed Sept.-Dec. by gravity and animals, largely by squirrels and rarely by water. Establishes as scattered individuals in shade or openings. A poor sprouter.
Swamp chestnut oak (cow oak) (*Q. michauxii* Nutt.)	Common in large creek bottoms and hummocks on best, well drained loamy ridges. Occasionally on a wet, silty clay, high flat. Rarely on best, most mature recent alluvium, but typically a tree of older alluvium sites.	Moderately intolerant.	Weakly tolerant. Seedling intolerant to flooding.	Seed dispersed Oct.-Dec. by gravity and animals, primarily squirrels. Seed germinates soon after seed fall. Best seedbed is moist and well-drained with a light cover of leaves. Seedlings require full sunlight for best development. Small stumps sprout well.

Table 1—Occurrence, shade and flood tolerance, and reproductive characteristics of the bottomland oak species[1]—Continued

Common and scientific name	Occurrence in bottomlands	Shade tolerance	Flood tolerance	Reproductive characteristics
Water oak (*Q. nigra* L.)	Widely on loam ridges in first bottoms and on any ridge and silty clay flats in second bottoms or terraces.	Intolerant.	Weakly to moderately tolerant. Prolonged submergence of seedlings during growing season will kill the trees.	Seed dispersed Sept.-Nov. by gravity, birds, animals, and water. Seedlings establish best on moist, well-aerated soil. Small stumps sprout readily.
Willow oak (*Q. phellos* L.)	Widely on ridges and high flats of major streams. Less common in creek bottoms. May form nearly pure stands of poor quality on hardpan terrace soils. Grows best on flats of old alluvium and on clay loam ridge of new alluvium.	Intolerant.	Weakly to moderately tolerant. Seedlings among oaks are one of the more tolerant to water, but prolonged submergence during growing season is fatal.	Seed dispersed Oct.-Dec. by gravity, birds, animals and water. Good seedling crops not unusual. Stumps under 12 in. in diameter sprout well.

[1] Adapted from McKnight and others 1981.

SILVICULTURAL SYSTEMS AND METHODS OF REPRODUCTION

Silvicultural systems integrate harvesting, regeneration, and intermediate operations in an orderly process for managing forest stands. Silvicultural practices are traditionally divided into two systems: even-aged and uneven-aged. A third system, two-aged, has been used with some success with Appalachian oaks (Beck 1987, Sims 1992). Although there are no published studies, the two-aged system also may have some application with bottomland oaks. The methods of reproduction employed under even-aged silviculture include seed tree, shelterwood, and clearcutting. Single-tree and group selection are methods of reproduction under uneven-aged silviculture. A discussion of each of these various methods of reproduction in relation to regeneration of bottomland oaks follows. A brief synopsis of the use of artificial regeneration to supplement natural regeneration of oaks is also presented.

Regeneration by the Seed-Tree Method

In the seed-tree method of reproduction, a small number of trees are retained to provide seed after harvest. This method favors wind-blown, light-seeded species (Toliver and Jackson 1989) and not heavy-seeded species, such as oak, in which seeds are dispersed for relatively short distances from the parent tree by gravity, birds, rodents, or sometimes water. Because most bottomland oak regeneration develops from advance reproduction present at the time of cutting or from the sprouting of stumps, there is little need or justification for seed trees (Johnson and Krinard 1976). Twenty-nine years after a seed-tree cut in bottomland sweetgum-red oak stands in Arkansas, Johnson and Krinard (1988) reported that the resulting stands were essentially similar to those produced through clearcutting. Most of the oak regeneration developed from advance reproduction and stump sprouts. Seed trees did not significantly contribute to the establishment of new seedlings.

Regeneration by the Shelterwood Method

The shelterwood method of reproduction is used to enhance the development of large oak seedlings prior to the final harvest cut. The classical shelterwood method usually employs a minimum of three cuts (Smith 1986):

(1) A preparatory cut of lower-crown-class trees to prepare a suitable seedbed.

(2) One or a series of partial cuts to encourage development of existing small seedlings.

(3) A removal cut of the overstory to release the advance reproduction.

Experience with oaks has indicated that the preparatory cut generally does not result in the establishment of new oak seedlings (Janzen and Hodges 1987, Loftis 1990). Although oak seedlings may appear after an occasional bumper crop of acorns, most seedlings become established as advance reproduction only over a period of years (Beck 1977). The shelterwood method for oak regeneration is primarily used to encourage the development of large seedlings from existing smaller ones, so that they will be able to successfully compete with other vegetation when the overstory is removed (Hodges and Janzen 1987, Loftis 1990).

Large red oak advance reproduction has been successfully cultured with shelterwood treatments in the Southern Appalachians (Loftis 1990). However, results with bottomland oaks have been highly variable. Hodges (1989) reported that, in practice, heavy shelterwood cuts favor the development of fast-growing, intolerant species rather than the oaks, while lighter cuts may encourage more tolerant and less desirable species. Factors contributing to the variable success of the shelterwood method to regenerate bottomland oaks as compared to oak regeneration in the Southern Appalachians include (1) higher site productivities; (2) a preponderance of tolerant species such as sugarberry, boxelder, beech, elms, maples, hickories, hornbeam, and hophornbeam; and (3) the unique hydrologic regime of bottomlands.

Shelterwood is the most flexible of all the methods of reproduction (Toliver and Jackson 1989); however, the timing of various cuts is critical for the continued development of oak reproduction. Treatment of the undesirable midstory and understory vegetation by herbicide or cutting is essential for the development of oak seedlings (Janzen and Hodges 1987, Loftis 1990). More research is needed before recommendations can be made on the shelterwood method of regenerating bottomland oaks, particularly in terms of the degree of competition control necessary, the number and intensity of cuts, and the interval between cuts.

Regeneration by the Clearcutting Method

The clearcutting method of reproduction involves the removal, in a single cut, of all trees larger than seedlings. However, this "complete clearcut" is different from a "commercial clearcut" in which unmerchantable stems that may interfere with the future development of regeneration are not removed. The primary advantage of the clearcutting method is that it provides the sunlight required for the development and growth of moderately intolerant to intolerant species such as oak (Kellison and others 1988).

Clearcutting is the most proven method of successfully regenerating bottomland oaks (Johnson 1979); however, there are qualifications. The success of clearcutting in regenerating bottomland oaks is dependent on the presence of adequate advance reproduction in the stand prior to cutting and the development of stump sprouts following cutting. Large seedlings of advance reproduction are essential to successful oak regeneration. The thousands of small oak seedlings that frequently occur in older stands simply cannot compete with faster-growing species upon release. Clearcutting has been successful in managed stands where one or more earlier thinnings have resulted in the development of large seedlings (Hodges 1989). Most oak regeneration failures following clearcutting are due to the lack of large, well-established advance reproduction and/or stumps capable of producing oak sprouts.

When clearcutting to regenerate oaks in bottomlands, the harvest should take place during the dormant season to maximize stump sprouting (Kellison and others 1988). Control of residuals either by herbicides or cutting is advocated, especially after a commercial clearcut (Golden and Loewenstein 1991), to reduce competition from undesirable midstory and understory species (Janzen and Hodges 1987). Clearcutting is also recommended where tree quality and stocking are poor (such as in high-graded stands) and there is little potential to upgrade the stand (Kellison and others 1988).

Clearcutting tends to initially favor the establishment and growth of shade-intolerant, fast-growing, light-seeded species, but species composition will gradually shift toward more mid-tolerants over time (Toliver and Jackson 1989). Oaks are often present, but typically inconspicuous, in the jungle of woody and nonwoody vegetation found during the early stages of development following clearcutting. However, two separate research studies on oak stand development have shown that bottomland oaks, although inconspicuous in the regeneration, eventually became prominent in the mature stand (Clatterbuck and Hodges 1988, Johnson and Krinard 1988).

Regeneration by the Single-Tree Selection Method

Single-tree selection involves cutting trees in all size classes to achieve a preplanned distribution of diameters and to create stands with an uneven-aged structure. This method is best-suited for shade-tolerant species that have the ability to regenerate and grow in the shade, such as beech and maple in the Northeast. When single-tree selection is continually applied to stands containing intolerant species, composition will gradually shift to more tolerant species (Johnson and Krinard 1989). When this method of reproduction is applied to mature bottomland oak stands, it usually leads to the development of future stands dominated by tolerant species, such as sugarberry, boxelder, hickories (pecan), elms, maples, and bays.

High-grading and diameter-limit cutting are often touted as single-tree selection. These abusive cutting practices of "taking the best and leaving the rest" are not true regeneration methods and are not to be construed as variations of the single-tree selection method of reproduction. These abusive cutting practices are not directed toward obtaining regeneration, and cutting does not occur in all size classes to maintain an uneven-aged structure. The assumption of taking the big trees to allow the little trees to grow perpetuates the development of advanced-aged, poorly formed, shade-tolerant trees that result in a progressively less-valuable stand.

There are few commercially valuable shade-tolerant bottomland species. Most bottomland oaks range from intolerant to intermediate in tolerance of shade

(Putnam and others 1960) and require some direct sunlight for successful seedling establishment and continued development. The light available to the forest floor in the small openings created by single-tree harvesting simply is not enough to ensure successful regeneration of oaks. Therefore, the single-tree selection method of reproduction is not recommended for bottomland oaks (Toliver and Jackson 1989).

Regeneration by the Group Selection Method

The group selection method of reproduction involves the removal of trees in small groups. The textbook interpretation (Smith 1986) is that cutting in small groups is regulated through volume control within size classes, following the uneven-aged system of silviculture. Size of opening generally ranges from 0.1 to 0.5 acre. The small openings created during these cuts usually fail to allow sufficient light to the forest floor for satisfactory establishment and development of bottomland oak reproduction. In bottomland forests, the trees that are able to regenerate in these small openings are usually of either a commercially undesirable understory species or a shade-tolerant species of low potential value.

Patch cutting is a combination of uneven-aged (group selection) and even-aged (clearcutting) silviculture where larger groups of 0.5 to 5 acres (usually 1 to 3 acres) are removed (Marquis 1989). An uneven-aged stand condition is produced by patch cutting consisting of many small, variously shaped, even-aged groups or patches within the stand. Management of timber is regulated by forest area. The forest stand under patch cutting exhibits "uneven-aged characteristics even though it is managed as a collection of small, even-aged groups" (Marquis 1989). Light available to the forest floor in these larger openings is sufficient to successfully regenerate bottomland oaks. The Tennessee Division of Forestry uses patch cutting as one management technique on its State Forests (Applegate 1991).

Anderson-Tully Company of Memphis, TN, successfully uses variations of group selection and patch cutting in its management of bottomland oak forests. Anderson-Tully practices classical uneven-aged silviculture (Smith 1986) by maintaining at least three age classes in its stands and by using volume regulation of the cut. The company's biggest challenge has been the regeneration of oaks under the uneven-aged system (Stephano 1992). Larger openings are used to provide optimum conditions for oak regeneration. This company also practices intensive control of midstory vegetation to further enhance establishment and development of oak reproduction.

Group selection requires a "hands-on" intensive silvicultural approach. Regulation of stand structure and development is complicated, time-consuming, and expensive. If used judiciously, however, group selection can produce the biological conditions necessary to allow the successful establishment and further development of bottomland oak reproduction.

Artificial Regeneration

Because large advance reproduction of oak seedlings is necessary for successful natural regeneration on bottomland sites, planning for regeneration is critical prior to harvest. When advance reproduction is insufficient, several to many years may be required to build up the amount and size of reproduction needed before harvest. Artificial regeneration can be used when advance reproduction is lacking and when the 5 to 10 years needed to establish advance reproduction are not available.

Artificial regeneration of oaks through direct-seeding, plantation culture, or enrichment/supplemental planting is discussed elsewhere in this symposium. A bulletin by Allen and Kennedy (1989) is an excellent source of reforestation information for bottomland hardwoods.

SUMMARY AND RECOMMENDATIONS

Natural oak regeneration in the bottomlands has been inconsistent. Most regeneration failures have been attributed to lack of advance oak reproduction. In general, advance reproduction of oaks must be secured in both sufficient size and number before the final harvest cut to successfully regenerate oaks on bottomland sites. The key consideration is to create favorable light conditions on the forest floor prior to final harvest. Control of the shade-tolerant competition in the midstory and understory is required for culturing bottomland oak reproduction. A pretreatment regeneration evaluation for bottomland oaks is necessary. When sufficient advance oak reproduction and sprout potential are present, a complete harvest or clearcut of all stems will usually regenerate the stand to oak.

Most stands range from closed-canopy stands with little advance reproduction to cutover, mismanaged, or unmanaged areas where species composition and tree quality are poor. In theory, the shelterwood method should nurture oak reproduction if oak seed sources are present. However, in practice, a heavy shelterwood cutting that creates gaps in the overstory usually favors the development of faster-growing intolerant species rather than oak, while in other instances shelterwood cutting actually encourages the growth of undesirable tolerant species already established in the midstory and understory. Both scenarios exclude optimum oak regeneration. Application of the shelterwood method for regenerating bottomland oaks has been discouraging with many more failures than successes. Single-tree selection also is not recommended for regenerating bottomland oaks because this method favors the growth and establishment of shade-tolerant species. Group selection can be used to regenerate bottomland oaks if the size of the opening is adequate to provide sufficient light to the forest floor to encourage the establishment and development of oak reproduction.

Figure 2 shows a generalized prescription for regenerating bottomland oaks. The pretreatment regeneration evaluation of figure 2 follows that presented in this symposium by Johnson and Deen (in press). No cookbook treatment for bottomland oak regeneration can totally account for the numerous biotic, abiotic, and anthropogenic factors which affect oak regeneration potential (e.g., site, species mixtures, past disturbances, flooding, fire, grazing, etc.). Practitioners interested in perpetuating oaks in the bottomlands need to evaluate existing stand and site conditions, the ecological requirements of the species, and the various prescriptions that are suitable for not only the establishment but the continued development of bottomland oaks.

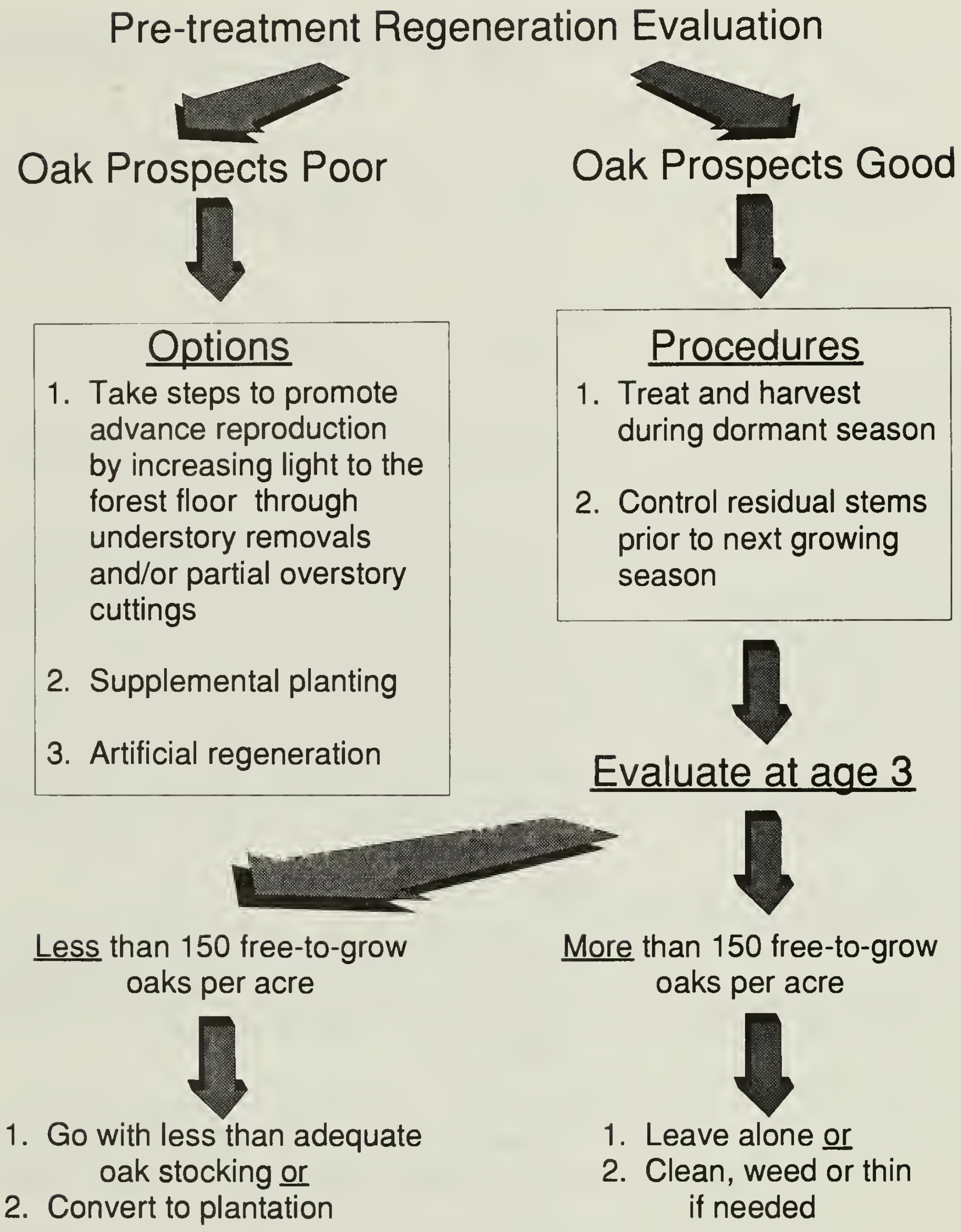

Figure 2—Regeneration procedures for bottomland oaks.

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Relative Growth of Oaks and Pines in Natural Mixtures on Intermediate to Xeric Piedmont Sites

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ABSTRACT

Increment cores and stem analyses from a growth and yield study in naturally regenerated pine-hardwood stands in the Piedmont were used to compare relative growth of oaks, pines, and other non-oak hardwoods on intermediate to xeric sites in that region. The primary focus in this paper is on the relative growth of only the oak and pine components. The stem analyses show that pines early in stand life grow faster in height than the oaks (a widely observed result), reaching an average maximum height advantage of 20 ft. by an average age of 32 years. Beyond this age, the stem analyses showed annual pine height growth slowing dramatically, falling below the rather steady 2 ft. per year observed for the oaks through age 70, thus reducing the average cumulative difference as the stands aged. For example, by age 55, the average 20-ft. cumulative height advantage of pine was cut in half, to 9.6 ft. We show that oaks attain basal area growth comparable to that of pines as early as age 15, and that beyond age 15, the oak growth advantage increased through stand age 70, outgrowing the pines by 70 percent between ages 60 and 70.

INTRODUCTION

Pine-hardwood mixtures are common in the Piedmont physiographic regions of Virginia, North Carolina, South Carolina, and Georgia. Unpublished data from the Forest Inventory and Analysis (FIA) Unit of the Southeastern Forest Experiment Station show that 1/3 of the Piedmont forest—7.1 million of 22 million acres—is in stands where 30 to 90 percent of the total basal area is in hardwoods, or 10 to 70 percent in pines. Although loblolly pine (*Pinus taeda* L.) is the dominant pine species, other yellow pine species are included in the estimates.

On these intermediate to xeric Piedmont sites, it is well known that pine growth exceeds that of oaks and other hardwoods early in stand life. This dramatic pine growth advantage is why we often hear these areas described as "pine sites." At the same time, oak coppice and advanced regeneration do well on these sites when they are present and are not aggressively controlled during site preparation. Oaks also outlive pines on these dry sites. Barring major disturbance, therefore, the oak component normally increases as stands on these sites age. In fact, it is common on eroded Piedmont sites for mortality of dominant and codominant pines to begin as early as age 40, thus speeding the composition toward oaks. Jones (1991) in his research on landscape ecosystem classification found oaks abundant in the late-successional stands he studied in the Piedmont. He also found that the oak species associations were indicators of a site-quality gradient. In summary, oaks regenerate naturally and persist on these sites. Their survival is site-specific, but they can generally be thought of as well-adapted to these sites.

Given this suitability of oaks for these sites, it is logical to ask how well they grow in long rotations relative to pines and non-oak hardwoods. Relative growth dynamics of the pine, oak, and non-oak species groups have not been examined for sawtimber rotations of naturally regenerated mixtures of pines and hardwoods. One objective of a major study we are installing, and the major focus of this paper, is to examine these growth dynamics.

METHODS

A growth and yield study in naturally regenerated mixtures of hardwood and pine has been initiated to study growth dynamics (Lloyd 1991). Fifty circular, 1/5-acre permanent plots measured in the first phase of this study form the dataset for this paper. Sampled stands contained from 93 to 182 sq. ft. of basal area per acre in merchantable and unmerchantable trees, and stand ages ranged from 20 to 79 years. Twenty one plots are on the Piedmont Ranger Districts of the Sumter National Forest and 29 are on the Clemson University Experimental Forest.

Diameters at breast height were measured on all trees, and merchantable sized trees (4.6+ in.) were tagged and mapped by azimuth and distance from plot center. Separate samples of hardwood and pine trees covering the diameter range on each plot were selected for measurement of total height. Although growth and mortality ultimately will be estimated by remeasuring these plots, recent growth was calculated from increment cores taken from merchantable-sized trees. Radial growth for the last 5 and 10 years was measured with a Bannister incremental measuring instrument. Radial growth data were used to estimate basal area of trees 5 and 10 years prior to plot establishment. Only survivor growth can be studied in this way.

Ten-year basal area growth of surviving trees was estimated as the difference between basal area of merchantable trees at measurement time and the calculated basal area of the same trees 10 years earlier. It was divided into components for pines, oaks, and non-oak hardwoods, and separate prediction models were developed for each species component. The same model form was fit to all groups. The predictor variables screened for these models were: (1) initial merchantable basal area in the given species group, (2) the species group's basal area as a proportion (ratio) of the total merchantable basal area, (3) the reciprocal of stand age, and (4) the cross-products of (1), (2), and (3).

Cumulative height growth differences were examined next. It has been widely observed that early height patterns favor pine. The goal here was to examine cumulative height over a longer time period. These height data were obtained by analyzing stems of pairs of one dominant or codominant oak and one such pine located near (not in) each permanent plot. Thus, two height/age curves were plotted for each plot. Each potential stem analysis tree was cored prior to felling to determine age and to seek evidence of previous suppression of growth. Trees with previous suppression were excluded. Substitutes were examined in the same way until a free-to-grow tree was found. Finding suitable trees was not difficult; we rarely had to go beyond the first choice. The resulting cumulative height/age curves were used to examine height-over-age patterns. In order to assess long-term patterns, the cumulative height data set was screened to include only plots in stands over 54 years old. Twenty plots (40 trees) met this criterion.

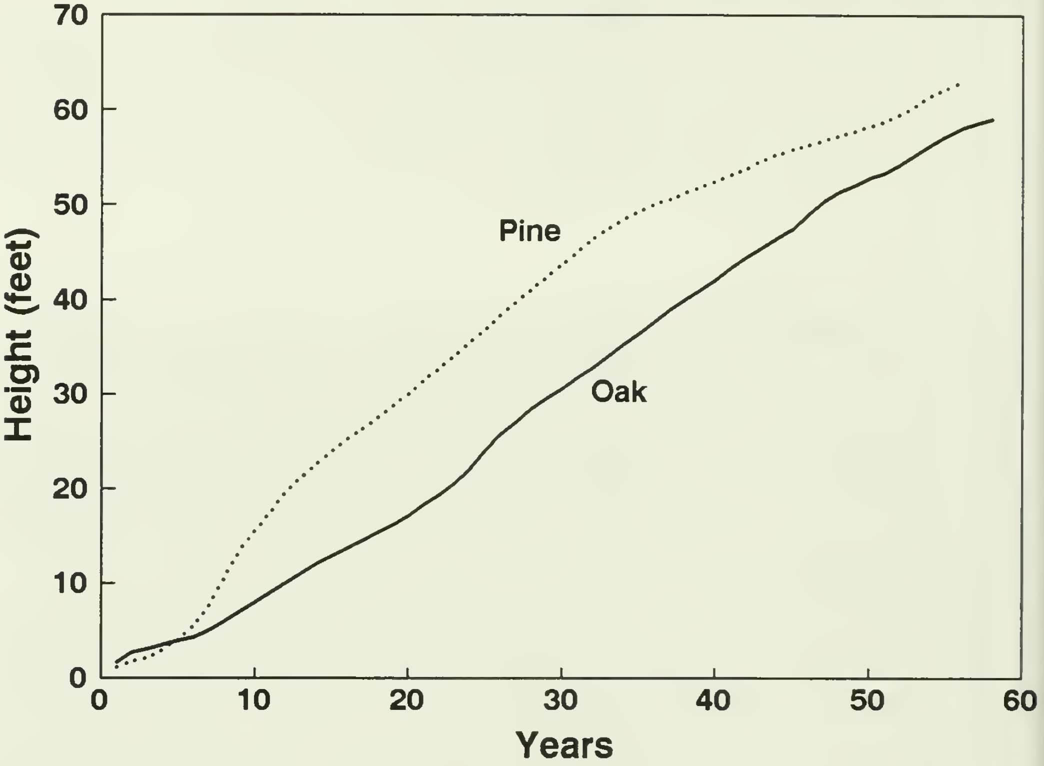

Figure 1—An example of a typical cumulative height pattern observed in stem-analyzed pairs of oaks and pines located near each of 50 permanent growth and yield plots in naturally regenerated hardwood and pine mixtures in the Piedmont physiographic region. The sample pine was always a loblolly, and the oak could be a dominant or codominant tree of good form from any of the oak species found on these sites.

The first step was to examine graphs of the height/age data for the pairs of oaks and pines on each plot. Figure 1 illustrates the predominant pattern observed for all plots. Because we estimated height at the end of every growing season by interpolation, it was easy to compute the height difference between oaks and pines over the life of the stand. Since pines where generally taller, we arbitrarily subtracted oak height from pine height, and then fit to each of the 20 data sets the simple quadratic polynomial expression

$$H_d = c_0 + c_1t + c_2t^2 \qquad (1)$$

where H_d is the difference in cumulative height between the pine and oak at an each age (t). We then used the estimates of c_0, c_1, and c_2 and the calculus of extreme values to estimate for each of the 20 plots the age at which the difference between pine and oak height was maximum and what the maximum difference was at that time in stand life.

The final analytical procedure looked at the average shape of the oak cumulative height pattern. All height/age data for the 20 sampled oaks were pooled into a single data set, and then the model

$$h_0 = e^a t^b \qquad (2)$$

was fit using nonlinear least squares. The variable h_0 is cumulative oak height at age t, and a and b are the model parameters to be estimated.

RESULTS

The model used to predict 10-year pine basal area growth (b_P) is

$$b_P = g_0 + g_1 B_P + g_2 P_P + g_3 B_P/t \qquad (3)$$

where B_P is the initial basal area of presently surviving pines as it occurred 10 years prior to plot installation, P_P is the proportion of total initial merchantable basal area (B) represented by pines (that is, $P_P = B_P/B$), and t is initial stand age. There are similar models for oaks (b_O) and non-oak hardwoods (b_N), where

$$b_O = g_0 + g_1 B_O + g_2 P_O + g_3 B_O/t \qquad (4)$$

and

$$b_N = g_0 + g_1 B_N + g_2 P_N + g_3 B_N/t. \qquad (5)$$

To further illustrate the definitions of the independent variables, the following relationships hold across the three models:

$$B_P + B_O + B_N = B \qquad (6)$$

and

$$P_P + P_O + P_N = 1. \qquad (7)$$

The R^2 statistics of fit for Equations (3), (4), and (5) above are 0.91, 0.75, and 0.77, respectively. R^2 values of 0.8 for regression models of periodic growth are considered good. The corresponding estimates of the model parameters (g_0, g_1, g_2, g_3) are (-3.079134, -0.21006, 32.38342, 6.670954) for pines, (1.879838, -0.0051275, 8.509635, 5.819824) for oaks, and (0.4226926, 0.1848599, -9.917444, 2.909263) for non-oak hardwoods. These estimated parameters were used in the appropriate model to predict components of 10-year growth for selected values of initial stand ages listed in table 1. It is not the goal in table 1 to predict for the actual initial stand conditions, but rather, to compare relative oak and pine growth performance. For this reason, the same set of P-values was used for each initial age, that is, $P_P = 0.4$, $P_O = 0.4$, and $P_N = 0.2$.

Table 1—Predicted periodic (10 years) basal area growth of survivors at four ages in pine-hardwood mixtures which have merchantable basal area composed of 40 percent pine, 40 percent oak, and 20 percent other hardwoods

	- - - - - - - Initial stand age[1] - - - - - - -			
Species group	15	30	45	60
	- - - - - - - - - ft.²/acre/10 years - - - - - - - -			
Pine	17.4	10.3	7.4	5.5
Oak	17.5	12.1	10.3	9.3
Other hHardwood	4.5	3.5	3.4	3.6
Total	39.4	25.9	21.1	18.4

[1] Total merchantable basal area at the beginning of each period was 80 ft.² at age 15, 90 ft.² at age 30, 100 ft.² at age 45, and 110 ft.² at age 60.

These proportions are all within the ranges observed in the data. Fixing these proportions permits direct comparisons because the oak and pine predictions of basal area growth come from the same initial basal area.

Table 1 shows that by age 15, the oaks were producing as much basal area growth as the pines for the same initial basal area. As the stands aged, the oak increasingly outgrew the pines in basal area through age 70. At that time, oaks were growing 70 percent more per 10-year period than the pines. The footnote for table 1 explains how the corresponding values of initial basal area were calculated. For example, for stand age 30, the observed data averaged about 100 sq. ft. of initial merchantable basal area (that is, B). Since P_P and P_O are both set equal to 0.4, the initial basal area components were 40 sq. ft. for both the oaks and pines. Thus, table 1 shows that for initial stand age 30, the 40 sq. ft. of oak grew 12.1 sq. ft. of basal area in the next 10 years (that is, from age 30 to age 40), while the 40 sq. ft. of pine basal area grew 10.3 sq. ft. in the same period. This growth advantage of the oaks increased with increasing initial stand age.

Figure 1 illustrates how pines on these Piedmont sites outgrow oaks. From Equation 1, we found that the average stand age of maximum pine/oak height difference was 32 years, and the average height difference at that point was 20.0 ft., with a quartile range of 17 to 22 ft. However, by stand age 55, the average pine/oak cumulative height difference was cut in half, to 9.6 ft. The pattern of dramatically slowing pine height growth after age 30 and steady oak height held generally across plots. It should be kept in mind that our working definition of pine-hardwood mixtures is not a closed pine overstory with a hardwood understory. We only work with stands in which the pine component is sparse enough to allow some light from above for the largest hardwood, even though they are shorter than the pines.

Visual examination of the pooled oak height data suggested a steady growth rate through stand age 70. We examined this average trend by fitting Equation (2) to the cumulative height data for the 20 plots that were 55+ years old. The nonlinear least squares estimates of the model parameters were 0.71 and 0.98 for a and b, respectively, and the value of e^a was 2.03. Since b was nearly equal to 1, the analysis suggests a rather steady 2 ft. of height growth per year. This average 2-ft. rate was suggested independently in another study (Geisinger and others 1989) of pine and hardwood regeneration. Table 2 shows oak height growth of 3.5 and 3.4

Table 2—Average heights of five species groups after four growing seasons for the winter-fell, no-burn treatment of the pine-hardwood regeneration study.

Growing season	Pine	Oak	Hickory	Blackgum	Other hardwood
			- - - - ft. - - - -		
1988	1.0[1]	3.5	1.7	2.8	4.0
1989	1.5	6.9	3.8	5.0	7.3
1990	3.3	8.9	5.2	5.9	9.1
1991	7.5	11.1	7.0	7.4	11.2

[1] Average height of seedlings planted in the 1988-1989 growing season.

ft. per year during the first two growing seasons, followed by a slowing to around 2 ft. per year the third and fourth growing seasons. Table 2 also reinforces the pine height growth pattern of lagging for around 3 years, and then dramatically accelerating. In this case, the pine grew 4.2 ft. in the fourth growing season.

CONCLUSIONS

As stated numerous times in this symposium, getting oak regeneration on xeric to intermediate sites is not hard when oak root stocks and advanced reproduction are present in clearcut stands. The data re-emphasize that after a growth lag, pines on these sites clearly outgrow oaks early in stand development. However, a longer-term look at height development tells a different story. It shows how pine growth slows dramatically after age 30, with oak rapidly cutting the height deficit. Although we do not have basal area growth data for very young mixed stands, this analysis shows oak basal area growth equaling that of pine by age 15. From that point, oak basal area growth increasingly surpasses the pines, reaching a 70-percent advantage between ages 60 and 70.

Given the increasingly important values of oaks for aesthetics and wildlife, the increasing stumpage prices for high-quality oaks, and the growing markets for low-grade oaks, managers of relatively dry upland Piedmont sites should take a close look at our results. We know that oaks are ecologically suited for these sites because they regenerate and live long lives there. Their growth performance in relation to pines is not impressive early in life, but our data indicate that they catch up later. Thus, they would appear to be sensible choices for sawtimber rotations.

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Regenerating Northern Red Oak on High-Quality Sites in the Southern Appalachians

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ABSTRACT On high-quality sites in the Southern Appalachians, dominant and codominant oak stems will be present in regenerated stands only when adequate regeneration sources exist in the mature stands to be harvested. These regeneration sources may be present in mature stands as advance reproduction or as stump sprout potential. Since oak trees tend to be larger and fewer in number on high-quality sites than on lower quality sites, and since large stumps are less likely to produce viable sprouts than are smaller stumps, advance reproduction is the most important oak regeneration source on high quality sites. The potential for advance oak seedlings to become dominant or codominant stems in the next stand increases with seedling size. Thus, the expected contribution of trees (as stump sprouts) and advance reproduction are both related to size. Methods are currently available to assess oak regeneration potential on high-quality sites in the Southern Appalachians. If the oak regeneration potential (and the potential for other species) in an existing stand is sufficient to meet management objectives, the overstory can be removed in one or more harvest cuts. If, however, the oak regeneration potential is not sufficient to meet management objectives, oak regeneration potential must be increased. Since very little can be done to increase the stump sprout contribution in the short run, the focus of activities must be to increase the contribution of advance reproduction. A technique currently recommended reduces stand basal area of the mature stand from below with herbicides, leaving a main canopy with no canopy gaps. This treatment allows *existing*, small oak seedlings to grow, but does not encourage yellow-poplar establishment and growth. The herbicide treatment prevents tolerant, mid-story stems from sprouting and removes them as a source of competition both before and after overwood removal. About 10 years after treatment, oak seedlings should be large enough to compete, and overwood removal can begin.

INTRODUCTION

Northern red oak is a very important tree species in the Southern Appalachians. The stands in which it occurs range from those dominated by red oak and other upland oaks to those dominated by deciduous species other than oaks. High-quality wood and relatively rapid diameter growth make red oak one of the most desirable sawtimber species, and its good, but infrequent, acorn crops are an important wildlife food. The problem of regenerating northern red oak on high-quality sites in the Southern Appalachians is well-documented and has been the subject of much research over the past several decades. In this paper I will discuss the overall research and the development of a successful regeneration technique.

THE PROBLEM

Thirty years ago, Charles E. McGee and Don Beck began a series of regeneration studies on the Bent Creek Experimental Forest that (1) identified the problem and (2) would provide important direction for future research (McGee 1967, Beck 1970, McGee 1975, Beck and Hooper 1986, Della-Bianca and Beck 1983, Loftis 1983a). The findings from these studies indicated that(1) oaks regenerated well after clearcutting on lower quality, xeric sites (where northern red oak seldom occurs); (2) oaks, and particularly northern red oak, performed poorly in competition with other species, particularly yellow-poplar and sprouts of shade-tolerant subcanopy species, on high-quality sites after clearcutting; and (3) regeneration under shelterwoods, over a broad range of residual basal areas, was essentially the same as would be expected after clearcutting. Concurrent research, in the Central States by Ivan Sander and Bryan Clark emphasized the importance of pre-existing vegetative structures—advance reproduction and stump-spouts—for oak regeneration (Sander and Clark 1971). And Sander was reporting that growth of advance reproduction following harvest was positively correlated with size of advance reproduction prior to harvest (Sander 1971, Sander 1972), a relationship we subsequently found important for red oak in the Southern Appalachians (Loftis 1990a).

McGee (1967) observed that under mature mixed oak stands, "seed germinate, the seedlings live for a few years, die, and are replaced by new ones. Cutting the overstory interrupts this cycle and stimulates growth." A study installed by Beck (1970) provides a quantitative description of the dynamics of red oak seedling populations in the absence of disturbance (figures 1,2). New seedlings become established whenever there is a good acorn crop, but after 10 years fewer than 10 percent of the seedlings have survived. And those survivors have grown very little (Loftis 1983b).

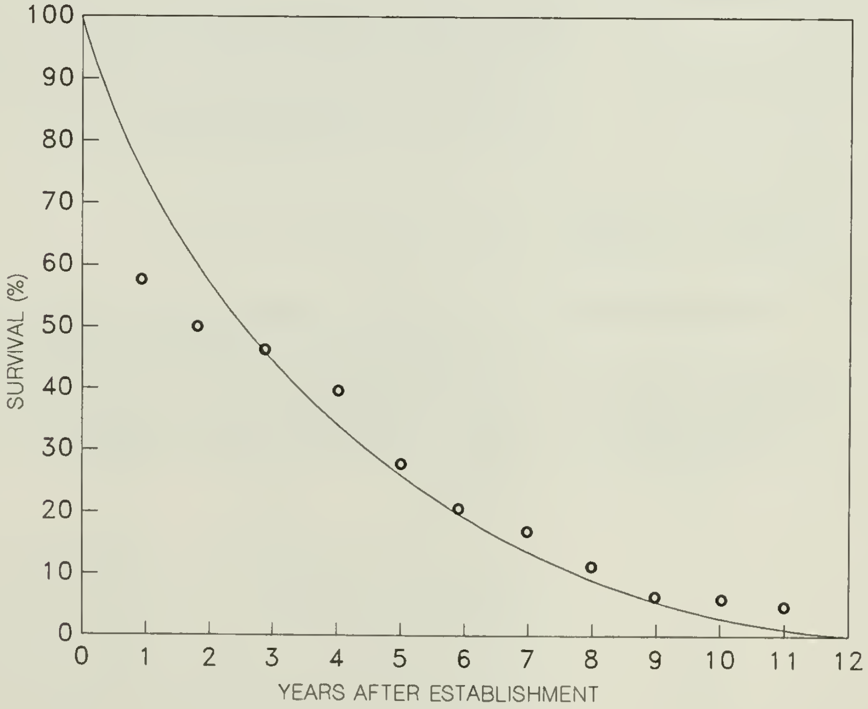

Figure 1—Survival curve for a cohort of red oak seedlings growing under undisturbed conditions under full canopy.

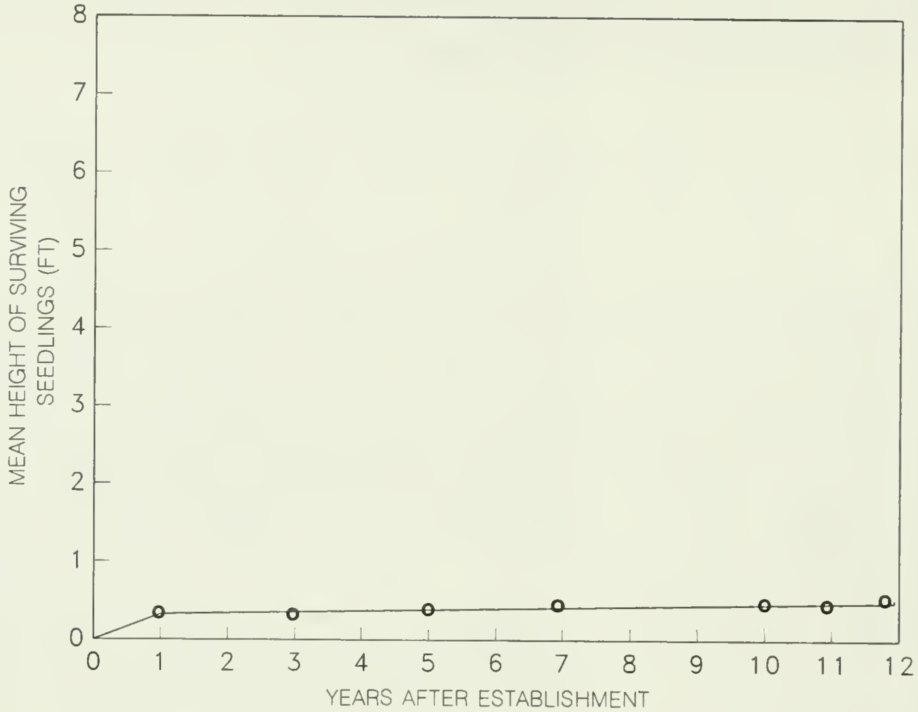

Figure 2—Mean height attained over time by a cohort of red oak seedlings growing under undisturbed conditions under full canopy.

It is now clear that regenerating red oak on high-quality sites is a problem in large part because the large advance reproduction necessary for maintaining a red oak component in the next stand is seldom present at the time of heavy regeneration cuts. Further, large red oak advance reproduction will not develop in the absence of disturbance sometime prior to harvest.

SOLUTION

Assessing Oak Regeneration Potential

In a stand where regeneration is being considered, and where maintaining a component of red oak in the regenerated stand is a management objective, the first step in meeting this objective is an assessment of existing red oak regeneration potential. As Johnson (this Proceedings) has indicated, regeneration potential is the expected contribution of existing advance reproduction and stump sprouts to the next stand.

Based on the relationship between preharvest size of advance reproduction and its development after harvest, we have developed a model that predicts the probability that an advance red oak stem will become dominant or codominant in the next stand as a function of its size and the site quality on which it is growing. These probability values and comparable values for stump sprouts adapted from Sander and others (1984) are presented in table 1.

Table 1—Dominance probabilities, at age 20, for northern red oak advance reproduction and stump sprouts.

Basal diameter of advance reproduction	Site index 70	Site index 80	Site index 90
(In.)			
0.1	0.01	0.00	0.00
0.2	0.02	0.01	0.00
0.3	0.03	0.01	0.01
0.4	0.05	0.02	0.01
0.5	0.07	0.03	0.02
0.6	0.10	0.05	0.02
0.7	0.13	0.07	0.03
0.8	0.17	0.09	0.04
0.9	0.20	0.12	0.06
1.0	0.24	0.14	0.07
1.1-1.5	0.34	0.24	0.14
1.6-2.0	0.44	0.38	0.28
d.b.h.		Stump sprouts[1]	
2- 5	0.49	0.42	0.35
6-11	0.46	0.39	0.32
12-16	0.38	0.31	0.24
17+	0.24	0.17	0.10

[1] Adapted from Sander and others (1984).

These probability values can be used to estimate the contribution of existing advance reproduction and sprouts produced by stumps if the stand were regenerated immediately by:

$$N = \Sigma\, n_{ij}\, p_{ij}$$

where

N = the expected number of dominant and codominant red oaks per acre at age 20 in the new stand

n_{ij} = the number of red oak per acre in the *i*th size class on the *j*th site index class

p_{ij} = the probability of red oak in the *i*th size class on the *j*th site index class becoming dominant or codominant at age 20.

For example, consider a mature stand on a site index of 90 with the following distribution of red oak:

Basal diameter	n(i) (stems/acre)	p(i) (from table 1)	N (expected number)
0.1	700	0.00	0
0.2	200	0.00	0
0.3	50	0.01	0.5
d.b.h.			
2-5	0	0.35	0
6-11	2	0.32	0.6
12-16	2	0.24	0.5
17+	5	0.10	0.5
		Total	2.1

Obviously, the stand under examination must be sampled to provide estimates of n(i) for advance reproduction (stems 2 in. or less in diameter at groundline) and for stems 2 in. d.b.h. and larger. Site index (j) must also be determined. Given the age of the study on which the probability model is based, the results are tentative. However, the models should allow the silviculturist to recognize, at the very least, those stands where the current red oak regeneration potential is inadequate to meet management goals.

If the current red oak regeneration potential is deemed adequate, the stand can be harvested in a single cut. However, if management objectives indicate the need to retain some overstory trees for a period of time, oak regeneration can still be successful if more than one cut is used to harvest the stand.

Increasing Red Oak Regeneration Potential

If current red oak regeneration potential is deemed inadequate to meet management objectives, silvicultural treatment must be used to increase the regeneration potential.

Shelterwood methods have long been recommended for regenerating oaks. However, as stated earlier, our experience with shelterwood cuts was disappointing. In shelterwoods with residual basal areas ranging from 25 sq. ft. to 66 sq. ft., oak seedlings did grow. But oak seedlings were soon overtopped by yellow-poplar seedlings and by sprouts of tolerant subcanopy species. Oaks did not benefit, relative to other species, from higher residual basal areas or longer periods of overstory retention. These results suggest that a shelterwood method to encourage red oak regeneration must (1) provide for the development of large advance red oak reproduction while preventing the establishment and growth of yellow-poplar, and (2) control competition from shade-tolerant, midstory species.

To address this question, we installed plots in well-stocked, mature stands with basal area reductions ranging from 0 to 40 percent of initial basal area. The basal area reduction was accomplished from below, with herbicides and deals in the most straight-forward manner with sprouting of understory species. A complete description of the methodology used in these studies and a presentation of early results can be found in Loftis (1990b).

The results of these studies after 13 years are very promising. We have defined residual stand densities that impede the establishment and growth of yellow-poplar while still providing enough light for the growth of small red oak seedlings that exist at the time of treatment. We did not find in these studies that shelterwoods enhance the establishment of new red oak seedlings.

If advance reproduction exists in the stand, but is not adequate to provide the desired oak component in the next stand (based on the model noted above), basal area reductions in the ranges of 25-30 percent on SI=90, 30-35 percent on SI=80, and 35-40 percent on SI=70 sites will result in development of larger advance reproduction. This treatment, should leave a stand with *no gaps* in the main canopy. Rarely would this initial treatment result in the removal of commercial material. The cost of application of this method is likely to be only marginally greater than the cost incurred when the same material is removed in other methods used to create well-stocked young hardwood stands. The initial treatment controls essentially the same vegetation that must be controled regardless of the choice of regeneration method. The difference is primarily one of timing.

Mean basal diameter growth of red oak seedlings resulting from the above treatment can be predicted (figure 3), and a future basal diameter distribution can be projected. For example, in a mature stand on a site index of 90 in which basal area is reduced by 27.5 percent, the predicted mean basal diameter growth would be 0.42 in. (figure 4). The data suggest that growth about this mean is normally distributed.

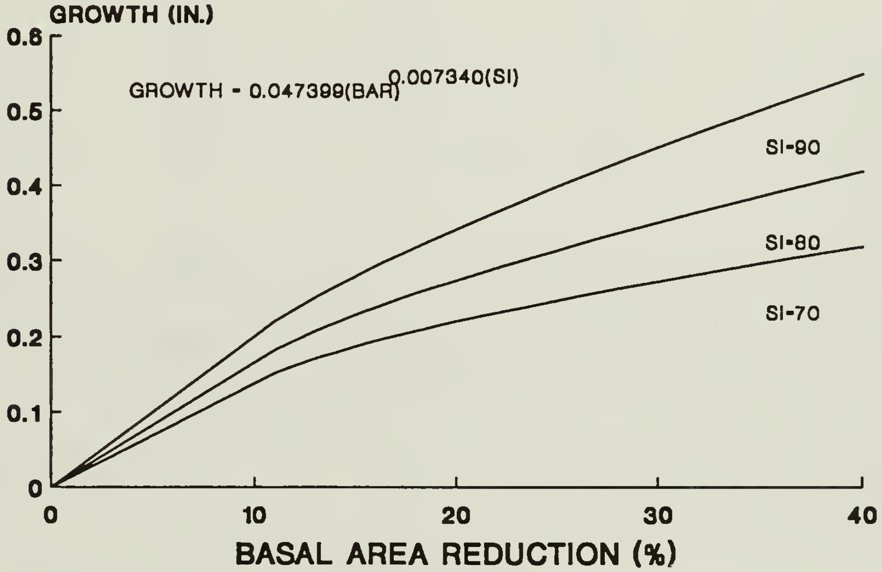

Figure 3—Mean basal diameter growth of red oak seedlings 10 years after treatment, as a function of site index and basal area reduction.

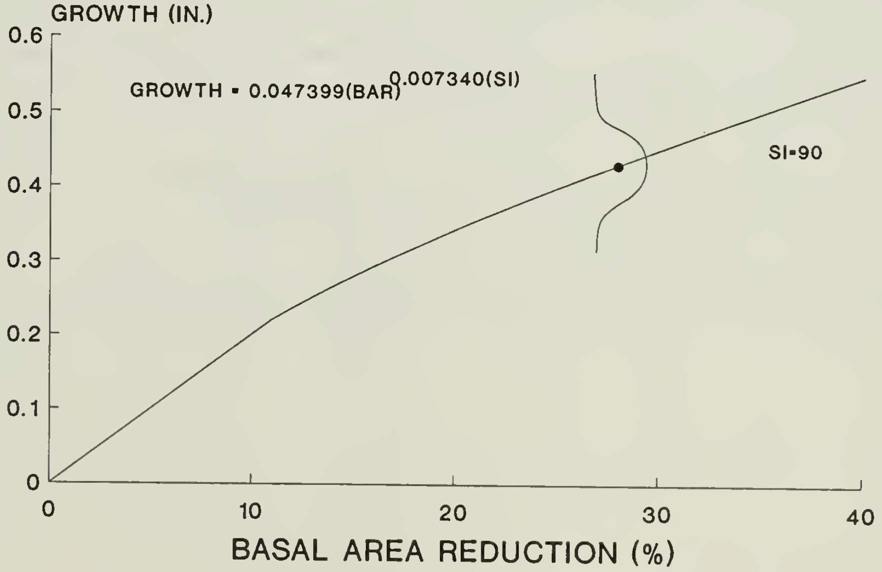

Figure 4—Predicted mean basal diameter growth of red oak seedlings 10 years after reducing basal area by 27.5 percent on site index 90.

By recovering the standard deviation from the equation:

$$SD = 0.08930 + 0.4314\ (\text{Growth})$$

a vector of transition probabilities based on the normal distribution can be generated. These transition probabilities are the probabilities that a seedling will grow 0.0 in., 0.1 in., 0.2 in., etc., in 10 years.

10-year growth transition probabilities (SI=90)

Growth	Probability
0	0.086
0.1	0.073
0.2	0.106
0.3	0.133
0.4	0.146
0.5	0.141
0.6	0.117
0.7	0.087
0.8	0.055
0.9	0.031
1.0	0.015
1.1	0.007
1.2	0.002
1.3	0.001

For a given population of seedlings, say:

Basal diameter		Number/acre
0.1	-	750
0.2	-	200
0.3	-	50

adjusted for survival:

$$\begin{array}{rcr} & \text{10-year survival} & \\ 750 & & 525 \\ 200 & \times\ 0.7 = & 140 \\ 50 & & 35 \end{array}$$

a future basal diameter distribution of red oak advance reproduction can be projected:

$$\begin{array}{cccccc} \text{Transition probability} & & & & \text{Future basal diameter distribution} & \text{Basal diameter} \\ \begin{vmatrix} 0.086 & 0 & 0 \\ 0.073 & 0.086 & 0 \\ 0.106 & 0.073 & 0.086 \\ 0.133 & 0.106 & 0.073 \\ 0.146 & 0.133 & 0.106 \\ 0.141 & 0.146 & 0.133 \\ 0.117 & 0.141 & 0.146 \\ 0.087 & 0.117 & 0.141 \\ 0.055 & 0.087 & 0.117 \\ 0.031 & 0.055 & 0.087 \\ 0.015 & 0.031 & 0.055 \\ 0.007 & 0.015 & 0.031 \\ 0.002 & 0.007 & 0.015 \\ 0.001 & 0.002 & 0.007 \end{vmatrix} & \times & \begin{vmatrix} 525 \\ \\ 140 \\ \\ 35 \end{vmatrix} & = & \begin{vmatrix} 45.2 \\ 50.4 \\ 68.9 \\ 87.2 \\ 99.0 \\ 99.1 \\ 86.3 \\ 67.0 \\ 45.2 \\ 27.0 \\ 14.1 \\ 6.9 \\ 2.6 \\ 1.1 \end{vmatrix} & \begin{matrix} .1 \\ .2 \\ .3 \\ .4 \\ .5 \\ .6 \\ .7 \\ .8 \\ .9 \\ 1.0 \\ 1.1 \\ 1.2 \\ 1.3 \\ 1.4 \end{matrix} \end{array}$$

Then, by applying the dominance probabilites to this projected distribution we can predict how much oak we would expect if this treatment is applied:

		Number/acre	X	Dominance probability	=	Expected number of dominant & codominant trees 20 years after harvest
.1	-	45.2		0.00		0
.2	-	50.4		0.00		0
.3	-	68.9		0.01		0.7
.4	-	87.2		0.01		0.9
.5	-	99.0		0.02		2.0
.6	-	99.1		0.02		2.0
.7	-	86.3		0.03		2.6
.8	-	67.0		0.04		2.7
.9	-	45.2		0.06		2.7
1.0	-	27.0		0.07		1.9
1.1-1.5	-	24.7		0.14		3.5
						Total = 19

By collecting information about the size distribution of red oak—from small seedlings to large trees—in an existing mature stand, the forester can explore the consequences of two potential prescriptions. First, the dominance probabilities (table 1) can be applied to the existing size distribution to predict the red oak component expected if the overstory removal in one or more cuts is begun immediately, with appropriate treatment of competing vegetation. Second, the existing size distribution can be used in the projection method presented above to predict the expected red oak component in the next stand if overstory removal is preceded by a basal area reduction from below followed by 10 years of advance reproduction development, as described above.

Limits of Application

The results are based on studies primarily of northern red oak in the Southern Appalachians. The stands in which this study were conducted would be classified as Northern red oak-White oak-Yellow-poplar, by far the most common mesic association in the Southern Appalachains. In this association, yellow-poplar is a very aggressive competitor. The association lacks a truly shade-tolerant canopy species, but does contain a number of shade-tolerant subcanopy species. Further, these studies were conducted in stands that were initially well-stocked, with complete closure of the main canopy and significant density of subordinate crown layers. While similar results have been reported in bottomland hardwoods (Janzen and Hodges 1985) and in more xeric oak systems (Graney 1989, Schlesinger and others 1993), the details of the method and almost certainly the models will be different.

Based on observations and measurements in some of the study plots (Loftis, unpublished data), black oak, scarlet oak, and chestnut oak respond to release similarly to red oak. White oak, however, does not.

CONCLUSION

If an objective is to maintain a red oak component on a site where we are considering regeneration, we have (1) a model to predict the future red oak component if the current stand were regenerated immediately by clearcutting or a heavy shelterwood cut; (2) a method to use when the predicted oak component falls short of that desired; and (3) models to predict the outcome of this alternative prior to its application. The use of the models does require that data be collected to enter into the models, however. By doing so the manager should have the information necessary to make a prudent choice of regeneration methods.

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Regenerating Oaks in the Central Appalachians

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ABSTRACT

In the Central Appalachians, regeneration of oaks on fair-to-poor sites is usually successful using even-aged silvicultural regeneration methods. However, for the good-to-better growing sites (red oak site index 70+), the establishment and development of natural oak regeneration is of major concern. Demonstrations of consistently successful methods for the establishment and subsequent development of oak reproduction, or both, on the better growing sites are limited. A promising shelterwood technique to stimulate oak seedling height growth has not been utilized to any extent. Keys to successfully establishing oak on the good growing sites include seedling establishment, stimulating seedling height growth, and controlling vegetation competition.

INTRODUCTION

The Central Appalachian forest is an estimated 23,000,000 acres that includes portions of southern Pennsylvania, western Maryland, West Virginia, western Virginia, eastern Kentucky, and southeastern Ohio. The Appalachians are mountainous with steep topography and a wide range of stand and site characteristics. A variety of slopes, moisture regimes, and soils are common. Access is difficult; however, the Appalachians are well known for the production of quality hardwood timber products. Often 25 commercial species or more occur in a given inventory. Oaks seldom exist in pure stands but more in mixtures with other hardwoods and conifers.

Historical events have played a major role in the establishment of the presently mature oak stands in the Central Appalachians. Repeated fires, death of the American chestnut, probable changes in wildlife and insect populations, and perhaps climatic conditions related to flowering are some of the factors that may have influenced availability of acorns and oak seedling development. Crow (1988) suggested a possible cyclic pattern related to the establishment of conifers within mature oak stands and, conversely, oak reproduction occurring within mature conifer stands. In the eastern forest, Carvell and Tryon (1961) concluded that disturbances reduce canopy densities and create openings, thus improving chances for the development of advance reproduction. Their hypothesis was influenced by a good correlation between amount of oak regeneration and amount of light reaching the forest floor.

Though oaks can be readily regenerated on fair-to-poor oak sites (northern red oak site index 50, 60, or below), oak regeneration problems occur on cove hardwood sites or stands with a site index of 70 and above. These good-to-excellent sites often contain a good source of available oak seed in the overstory. Because regenerating oak on the fair-to-poor sites is not a major problem in the Central Appalachians, information in this paper will focus on the better hardwood growing sites.

Establishment of oak simply cannot occur without available reproduction from stump sprouts, advanced reproduction, planted seedlings, or acorns. On these better oak sites, there are at least three oak reproduction understory situations: (1) oak seedlings or saplings not present; (2) some oaks present but inadequate (usually not tall enough); and (3) oaks present and tall enough (4.5 ft.) to respond after removal of the overstory. However, in reality, the situation where numerous oak understory stems are greater than 4.5 ft. rarely occurs. Of course, when oak stems are not present in the understory, there are two obvious choices—wait for a bumper seed crop to occur or plant seedlings or perhaps acorns. Assuming overstory trees are mature enough to produce acorns, a bumper seed crop means having enough acorns to feed all the wildlife, insects, etc., and still have acorns available for seedling establishment. However, these bumper seed crops are rare and not predictable. Regardless, the presence of oak regeneration does not assure success.

Another factor to establishing oak is to ensure that existing oak seedlings and saplings produce an increased and continuous height growth response. Getting oak seedlings to increase in height is costly and not an easy task. Too often, the release methods used stimulate competing vegetation at the expense of the oak stems or the oak seedlings respond poorly to the release technique. Released oak seedlings are exposed to adverse weather and often damaged by spring frosts and freezes (McGee 1973).

Another key to establishing oak is the need to keep the oak stems competitive as the young stand develops so that some oaks will become a component of the mature stand.

SUCCESSFUL REGENERATION METHODS AND SILVICULTURE SYSTEMS

On fair-to-poor growing sites, oaks can be consistently regenerated by even-aged silvicultural methods such as clearcutting or shelterwood (Roach and Gingrich 1968, Sander and Clark 1971). On the better oak sites, regenerating oak becomes more difficult and inconsistent. There has been much theoretical discussion about using commercial shelterwoods to reproduce oak seedlings on the better growing sites (Sander and others 1983). However, successful on-the-ground demonstrations are limited. In most cases, seed crops were inadequate or the initial cut of the shelterwood stimulated competing stems, such as yellow-poplar, that quickly overtopped established oak seedlings. Wolf (1991) reported oak regeneration success (red and white oak families) using the shelterwood system on Glatfelter Pulp Wood Company land in south-central Pennsylvania. Failures were related to not controlling understory vegetation, the white-tailed deer, or both. Oak site index for the areas ranged from 55 to 75 (fair-to-good growing sites). Site index 75 is near the lower range for oak regeneration problems in the Central Appalachians.

Success using Wolf's shelterwood approach included:

- Start with mature, fully stocked stands with a number of seed-producing oak trees.
- Use stands having terrain well suited for maneuvering harvesting equipment.
- Complete initial seed cut within 3 years after a bumper seed crop.
- Leave 55 to 60 percent oak crown cover in the residual overstory.
- Select residual trees based on distance between crowns.
- Control undesirable shade-tolerant understory competing vegetation.
- Complete overstory removal cut when 70 percent of milacre plots are stocked with at least one red oak seedling 2 ft. tall. This seedling height usually occurs within 5 to 10 years after the initial cut.

Loftis (1990b) used a "noncommercial" shelterwood method to stimulate growth of existing advanced red oak reproduction in the Southern Appalachians. Success was found by reducing basal areas in mature, fully stocked stands to 60, 65, and 70 percent of the initial stand basal area for red oak site index areas of 70, 80, and 90, respectively. Trees were removed from beneath the main crown and herbicides applied to the cut stumps or stems were basal sprayed. Little to no cutting was done in the main canopy. These treatment methods prevented yellow-poplar, a primary competitor of red oak, from becoming established before the final removal cut (Loftis 1990b, O'Hara 1986). Also, the herbicide treatment eliminated most sprout competition from shade-tolerant understory species after the final removal cut. However, application of this technique is minimal in the Central Appalachians due, perhaps, to the establishment of other desirable (non-oak) reproduction, transfer of technical knowledge, gypsy moth, few to no oak seedlings present, cost, or just lack of confidence that the technique works or will work for the given situation.

While consulting with others in the Central Appalachians, a few success stories were reported related to regenerating red oak on good-to-excellent sites. For instance, there are some successful oak regeneration areas on Westvāco properties in south-central West Virginia. Initially, almost no advanced reproduction was present in these stands. Over the years, partial cuttings were done with the idea of eventually clearcutting the stands. Forest managers believe that these partial cuttings increased the establishment of the advanced oak reproduction. There are a few on-the-ground examples where some overstory trees were removed, and advanced oak stems are successfully competing with other regeneration for the future stand. Currently, it appears that some oaks will be codominant trees in the future stands. Precommercial cultural techniques, such as using herbicides to favor the oaks, are being tried experimentally in these stands. Most of the competing vegetation develops foliage earlier than the oak; thus, foliar-active herbicides are used to remove the competition before oaks break bud. Preliminary results are encouraging.

Where no oak seedlings are present in the understory, some managers suggest eliminating the heavy shade understory to allow patches of sunlight to reach the forest floor. This treatment may allow more opportunity for acorn germination and seedling development. Though this application might work for some situations, it is very uncertain. Where seed-bearing oaks are present and when a bumper acorn seed crop occurs, oak seedlings will become established everywhere throughout the understory on all sites. These seedlings will usually remain for a couple of years and then rapidly begin to die. Thus, managers have a few years to use available techniques to stimulate understory oak height growth. Unfortunately, bumper red oak acorn crops do not occur often. During the last 30 years, there has been a maximum of 3 to 4 bumper crop years in the Fernow Experimental Forest near Parsons West Virginia—when walking in the woods is like roller skating on acorns during the winter and spring after the fall seeding.

Some forest managers indicated that getting established advanced oak regeneration to respond might be done by felling the understory trees, such as sugar maple, striped maple, and possibly hemlocks. Hardwood sprouts could be a problem and, if so, herbicides could be used as necessary. This is similar to the Loftis (1990b) approach.

On the Fernow Experimental Forest, a shelterwood study was established 8 years ago for the purpose of establishing red oak seedlings and/or stimulating seedling development. Initially, 16 two-acre plots were established on good growing sites (red oak site index 70) and the following year 12 additional plots were established on excellent growing sites (site index 80). Various overstory residual stocking percent treatments were used including 45, 60, 75, and 100 percent (no cutting). Also, understory treatments were done using herbicides for seedlings, saplings, and pole-size trees up to 10 in. d.b.h. (excluding oaks). Replicated plot treatments included no understory or overstory treatments; understory but no overstory treatments; understory and overstory treatments combined. Each plot was underplanted with 50 red oak seedlings during the spring immediately after the dormant season cutting treatment. Red oaks were the main residual trees after the initial shelterwood cuts. The fall before the initial treatment period appeared to be a reasonable acorn seed year. Before the initial shelterwood treatment, two of the plots on the site index 70 areas had hundreds of advanced red oak seedlings 2 ft. tall and taller. At the time, it was thought a clearcut would have been as successful as a shelterwood due to the height of the advanced oak stems. A few other plots on this site index 70 area had some small advanced red oak seedlings present before treatment.

The two plots with oak stems 2 ft. tall and taller were treated with a 45 percent residual shelterwood overstory removal. Also, an understory basal spray herbicide treatment was used. Oak reproduction dominated these areas and after 5 years, a major blowdown occurred in this portion of the study area. Eight years after treatment, the remaining overstory trees were removed. Red oak will dominate the future stand. However, for the remaining shelterwood and/or herbicide treatment plots, oak regeneration is absent; if present, it is less than 2 ft. tall and often shaded by a dense layer of vegetation. Recently, on some plots, the reproduction layer of competing vegetation was treated with herbicides in an effort to maintain and stimulate the oak seedlings to respond. Unfortunately, for the Fernow study, the timing of the initial understory-overstory treatments did not coincide with a bumper acorn seed crop. We should have waited until natural seedlings were well established before applying the study treatments; however, we thought the planted seedlings would respond. Presently, after 8 years, surviving planted oak seedlings average less than 2 ft. tall, but most died due to deer browsing, weather, and insects.

Thus, there has been some success in the Central Appalachian region in regenerating oak, primarily red oak, on the good and better growing sites. However, in general, specific methods to establish oak on these sites tend to be more happenstance or theoretical than actual. Establishing oak seedlings is the most important initial concern. Once natural oak seedlings (resulting from a bumper acorn seed crop) are established, techniques to stimulate height growth of the seedlings become most important. Methods of stimulating the height growth of existing understory oak seedlings involve controlling (removing-killing) other competing understory seedlings, saplings, and pole stems. Though expensive, the technique has potential. The purpose is to provide enough light for oak seedlings to respond yet minimize the establishment of yellow-poplar. Kittredge (personal comments) indicates that stimulation of oak regeneration height growth is important, but he believes the oak seedlings have to spend some portion of time initially growing slowly in the understory while developing good roots. He also indicates there may have been some oak regeneration mistakes made in the past where foresters had excellent seedlings established from bumper acorn crops but the overstory canopy was opened too much, too soon. Kittredge indicated the new seedlings were not able to take advantage of the light due to poor root development.

A history of repetitive fires to regenerate oaks has been related to the presence of oaks in the current overstory stands on good-to-excellent Appalachian hardwood growing sites. However, fire specifically to regenerate oaks may not be practical in the Central Appalachians.

ANTICIPATED PROBLEMS

Anticipated problems to the establishment of oaks on the good-to-better growing sites are related to the use of herbicides and possibly the use of fire. Herbicides and fire are means to control the competing vegetation. Continued political constraints and social concerns related to using herbicides may result in limited to perhaps no use of herbicides on public forest lands. Fire, if successful, would be a difficult tool to apply from a practical basis. Many of the good and better growing sites would be difficult to burn under prevailing weather conditions; more importantly, when these moist sites would burn, the fire hazard in the general area would be too high for safe use of controlled burning. Residual stand damage as a result of the hot fire would be major (Wendel and Smith 1986). Too, air pollution resulting from prescribed fire is of great public concern.

First Key Factor

Problems in establishment and development of oak regeneration relate to seed production, predation, competing vegetation, and stimulating seedling height growth. Seed production for oaks, particularly red and white oak, is very sporadic and unpredictable. To be successful in establishing oak seedlings, good-to-bumper acorn crops are a necessity. When major acorn crops are produced, there are enough acorns to feed the wildlife, etc., and still have many acorns to germinate new seedlings. However, planning forest management practices around production of acorns has too much uncertainty in the Central Appalachians to be effective.

If techniques to establish oaks on these good-to-better oak growing sites are perfected, there are still two overriding factors that will have a major impact on the oak regeneration programs: deer and the gypsy moth. Deer populations in certain areas of the Central Appalachians are so high, that understory browse lines are quite visible. As the deer population increases, there will be public, and thus political, resistance to increasing deer control measures for the sake of forestry purposes. In the future, much of the Appalachian forests could have a browse line similar to parts of the northeastern forests. When this occurs, it is too late for quick remedial actions.

Gypsy moths are another concern. This insect presently has no effective natural controls in the United States, though there is a fungus from Japan that has possibilities (Andreadis and Weseloh 1990). Thus, once present, the gypsy moth remains in the forest indefinitely. Oaks are the preferred food source for the gypsy moth and tree mortality is usually high following one or two periodic defoliations. As the moths steadily progress from New England into the Southern Appalachians, and if the Asian gypsy moth begins to progress from the west to the east coast, it is reasonable to ask why do we even consider establishing and growing oaks in the future stands? The answer to this pertinent question is not obvious. Forest managers will continue to assess the situation and will provide the answer by their actions. For those wanting to manage oaks, the establishment of advanced oak reproduction and the tending and culturing of these stems will be an acceptable management objective. Methods for controlling gypsy moths will become part of the management scheme. Also, efforts could be made to stimulate oaks to retain vigorous crowns in mixed hardwood stands that might withstand periodic defoliations (Gottschalk 1988). However, these recommendations/concepts are in the research stage.

In reality, the presence of gypsy moths will have a long-term effect on the silvicultural practices used in eastern hardwood forest management. However, some natural resistance to defoliation will occur and, though the oak composition in the Central Appalachian forest stands will be significantly reduced, it is not expected to be completely eliminated by the moths. Many oak trees still remain associated with the gypsy moths. The forest manager's inability to reproduce oak on these good growing sites may have a negative impact on moth populations. The stands will become more mixed with other hardwoods, thus minimizing the attractiveness to the moths. Stands on forests with fewer oak should not be able to sustain the moths at frequent, epidemic levels (Steve Jones, personal comments).

Second Key Factor

Once acorns germinate and seedlings become established, competing vegetation often can become a major deterrent to their development. Oak seedlings commonly have very slow height growth during their early years of development. Treatments to stimulate oak height growth often trigger an overwhelming response by competing vegetation or can expose the seedlings to frost or freezing problems. There is a fine line between just enough light only to stimulate oak seedling growth and too much light, thus stimulating shade-intolerant reproduction. Apparently shaded oaks will start growth in the spring before the canopy fully leafs out (McGee 1974). A noncommercial shelterwood technique described by Loftis (1990b) is the proposed approach for use in the Southern Appalachians.

COSTS, BENEFITS, AND RELIABILITY

Establishing natural oak regeneration on the good-to-better growing sites can be expensive and results are uncertain. There are a number of practices to consider. In the Central Appalachians, I suggest waiting until the natural oak seedlings are established before applying any cultural practices. This could prevent future problems, especially if the anticipated seed crop is a bust. Felling saplings and poles in the noncommercial shelterwood technique can cost from $30 to $40 per acre, while the cost to treat poles and saplings with herbicides approaches $60 per acre or more. However, effective herbicide treatments eliminate stump sprouts. Remember, do not consider this non commercial shelterwood approach until natural seedling establishment has occurred.

If natural seedling establishment is rare, consider planting bare-root seedlings following clearcutting. All saplings and poles should be cut during or following removal of the commercial stems. Cutting during the mid to late summer and early fall is preferable in that sprouting would be minimized. If saplings and poles are felled during logging and left on the ground, cost or credit to the logger would average about $30 to $40 per acre. If this site preparation occurs after logging, the contract cost would increase to at least $60 per acre due to the presence of slash. However, depending on the local market situation, the minimum size for merchantable trees could range from 6 to 12 in. d.b.h. Some or all of the pole size trees might be sold, thus reducing the cost.

Also, use plastic tree shelters on the planted and even any natural seedlings that might be present. These shelters protect the seedlings from deer and other animal damage while providing a greenhouse effect that stimulates tree growth. Currently 2-0 special root-pruned seedlings cost about $150 per 1,000 (15¢ per seedling). These "special" seedlings are usually root pruned in early August during the first year in the nursery seedbed and only 2-0 seedlings with at least 0.4 to 0.5 in. root collar diameter are planted. On a good planting site, one person could plant about 200 seedlings per day. Thus, if the hourly wage were $7, it would cost $56 to plant 200 seedlings per 8-hour day, plus another $30 for the seedlings, for a total cost of $86 (43¢ per seedling).

A 5-ft. tree shelter would need to be installed around each planted seedling. If the deer population were low, perhaps shorter shelters could be used. Current costs of 5-ft. shelters vary from about $2 to $6 depending on brand and quantity purchased. Also, in most instances, 1- x 1-in. sharpened white oak stakes are used to hold the shelter in place. These stakes cost approximately 50¢ to 60¢ each. Two people can install about 200 shelters per day at a labor cost of $14 per hour using the $7 per hour rate. Using a $4.50 cost for each shelter-stake, planting 30 seedlings per acre, and installing a shelter on each seedling would cost $164.70 per acre (table 1). With the planted seedling-shelter on a forested site, there is a strong possibility that one or more herbicide applications will be necessary to control competing vegetation on the good-to-excellent Appalachian hardwood sites. This could involve applying herbicides in a 10-ft., or larger, radius around each shelter.

Planting acorns using shelters has potential. If acorns are used, planting cost will be reduced; however, the cost of purchasing and installing shelters would be similar.

The artificial regeneration technique has some promise, and on the Fernow Experimental Forest, approximately 40 percent of planted (2-0) and a few 1-year-old natural seedlings have grown out the top of 5-ft. shelters in clearcut areas during the first year. However, there is uncertainty as to whether this seedling height growth will continue sufficiently to keep above, or at least compete with, the natural reproduction on these good-to-excellent cove hardwood sites.

Table 1—Estimated cost of planting red oak seedlings and plastic shelters

Materials, Labor	Cost
2-0 special root-pruned seedling	$150 per 1,000
Labor rate	$7 per hour
Shelters, 5-ft.	$2-$6 per shelter
Stakes, 5-ft. 1- x 1-in. white oak	50¢-60¢ per stake
Example:	
Plant 30 seedlings per acre (15¢ per seedling)	$ 4.50
Labor cost (28¢ per seedling)	8.40
Install 30, 5-ft. shelter-stakes per acre ($4.50 per shelter-stake)	135.00
Labor cost (56¢ per shelter-stake)	16.80
Total cost per acre	$164.70

BEST RECOMMENDATIONS TO ACHIEVE VARIOUS OAK REGENERATION GOALS

On drier, poor-to-fair sites, where mature oak trees occur, oaks can be reproduced through clearcutting or any other form of even-aged silviculture. However, for the moist, good-to-better growing sites, it has been difficult to reproduce oak from mature oak stands. With change in site quality, there is a change in species composition and the species differ in their ability to sprout. Sprouting is a function of size, age, growth rate, etc. On poor-to-fair sites, chestnut and scarlet oaks may dominate. On fair-to-medium sites, scarlet, chestnut, black, and white oaks may be dominant. On good sites, northern red, white, and black oaks will occur, and on the best sites, northern red oak is usually the only one that will compete (David W. Smith, personal communication).

Ideally, when wanting to reproduce oak stands, if 435 well-established, advanced oak stems per acre, over 4.5 ft. tall are present (including potential stump sprouts) and free from shade of a mid-canopy, then clearcutting will be successful (Sander and Clark 1971, Sander and others 1983). However, it is rare to find advanced oak reproduction more than a foot tall on the good-to-excellent Appalachian hardwood sites. Where these small oak stems occur, a potential practice is to reduce the overstory canopy by applying herbicides to all sapling and pole trees (1 to 10 in. d.b.h.) to give these small oak seedlings room to grow (Loftis 1990b). Usually no trees are cut in the upper crown canopy. The objective is to provide just enough light to let the oak grow without allowing other competing vegetation such as yellow-poplar to become established. Northern red oak advanced seedling growth response is based on root collar diameter and the probability of these stems being in the dominant or codominant crown class 20 years after clearcutting (Loftis 1990a). Using this probability concept, silvicultural decisions, such as when to complete the final cut, are based on the desired number of dominant and codominant red oak stems the landowner wants in 20 years. This is where the uncertainty occurs. Once the overstory is removed, will the oak stems compete with the associated vegetation? In the Central Appalachians, there are few stands on these good-to-better growing sites that have oak reproduction of proper size to consider removing the overstory.

Another technique suggested for use in openings is to clip the tops of established natural seedlings near groundline, then to protect these clipped seedlings by installing plastic shelters (Kittredge and Kelty 1992). On the Fernow, tree shelters were installed on a few natural seedlings after clearcutting and the seedlings responded.

For most of the Appalachians, a realistic objective for reproducing of oaks on the good-to-excellent growing sites is to reproduce *some* oak in the next stand. Thus, guidelines will be less stringent than those recommended for reproducing a fully stocked oak stand.

In general, bumper seed crops are needed to provide enough acorns to overwhelm the rodents, mammals, insects, and other users to allow for the establishment of the young seedlings. Where no oak seedlings exist in the understory, choices are limited if an oak component is an objective in the next stand. Managers will have to wait for a bumper seed year. Planning forest management programs based on climatic or natural occurrences is uncertain. There is another and yet unproven technique that may work. Plant "special" 2-year-old northern red oak seedlings that are root-pruned during early August the first year in the nursery seedbed. Taproots are pruned 6 to 8 in. below the ground, resulting in the development of a more fibrous root system (Johnson and others 1986). Since the special seedlings have a large root system, it is very important that good planting techniques be used. A major problem in planting these large seedlings (root collar diameter at least 0.4 in.) is providing a planting hole of sufficient size to accommodate the root mass. If a hole is too small, the roots are easily cramped and become "j-shaped," and seedlings die or have little growth potential.

Planting perhaps 30 to 40 "special" red oak seedlings per acre in a clearcut area before the start of the first growing season after a dormant season cut is worthy of consideration. Immediately after planting, install at least a 5-ft. plastic shelter around each planted seedling. Before installing the shelters, seedlings could be top pruned about 6 to 8 in. above the ground. However, to date, the best results we have on the Fernow Experimental Forest are where the planting stock was top pruned at 1.5 ft. This was done in the seedbed immediately before the 2-0 seedlings were lifted for distribution. Our ideal objective is to have each seedling growing out the top of a 5-ft. shelter in 1 year. Though specific results are not available, recently stratified red oak acorns were planted during two different spring seasons on the Fernow Experimental Forest. Shelters were installed immediately after each planting. Rodents did not damage or remove the acorns and the acorns developed into seedlings.

CONCLUSIONS

In general, I believe successful regeneration of red oak would be to have 15 to 20 codominant oak stems per acre on good-to-excellent Central Appalachian hardwood sites when the even-aged stands are 20 years old. A probability of survival for planted seedlings without shelters is to plant four seedlings to obtain one (Johnson and others 1986). With shelters, this proportion should be less; however, this is conjecture and not based on research information. Remember, the objective is not to convert these good-to-excellent central hardwood sites to oak stands, but simply to ensure that there is an oak component in the future stands—perhaps at levels similar to the present portions.

Thus, there are two general objectives concerning oak regeneration on the better sites in the Central Appalachians:

1. Establish oak seedlings where none exist;
2. Stimulate oak seedlings to respond in height growth following establishment, in order to compete with associated vegetation and become part of the future stand overstory.

If natural oaks are present in the understory, a possible technique to stimulate these seedlings to develop is the noncommercial shelterwood technique reported by Loftis (1990b) for the Southern Appalachians. If natural oak seedlings are not present in the understory, wait for their establishment as a result of a bumper seed crop or plant oaks immediately after clearcutting. In both instances, once seedlings are established and if clearcutting is used, install a plastic tree-shelter around each seedling. Do not install brown plastic shelters on red oak seedlings where a portion of the overstory shelter remains after cutting.

The establishment of natural oak seedlings and their subsequent stem development are keyed to bumper acorn seed crops and timing of cultural practices. Cultural practices should not be applied until after the natural seedlings are established in the understory. In the past, understory-overstory cultural techniques have been applied in anticipation of bumper seed years. In most cases, these seed crops did not occur and their absence resulted in additional understory regeneration problems.

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Artificial Regeneration of Oaks

A Historical Perspective of Planting and Seeding Oaks: Progress, Problems, and Status

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ABSTRACT

Historically, the planting and seeding of oaks was done for species conversion on forest lands and for reforestation of old fields. More recently artificial regeneration has been used to supplement natural regeneration prior to or following stand removal, to introduce genetically superior individuals, to reforest drastically disturbed lands, and to provide species diversity in naturally occurring or man-made wetlands.

This paper describes the progress that has been made since 1971 in solving the problems which inhibit the successful regeneration of oaks by planting and direct seeding. Reference to current literature is used to describe the state of knowledge or status of artificial regeneration.

Advances in oak regeneration have greatly improved the chances of a successful planting, but a degree of uncertainty remains. Artificial regeneration offers the best solutions to oak regeneration problems in the future. It is imperative to press forward for breakthroughs in genetics, economics, and the biology of early growth. Today, land managers should proceed with the planting and seeding of oaks but they should consider all the information provided in this symposium and proceed with caution.

INTRODUCTION

The purpose of this paper is to present the current status of artificial regeneration of oaks by direct seeding and seedling planting. In the course of this presentation I have attempted to identify some of the problems that remain and provide some suggestions for future research. I have divided artificial regeneration into two major topics—direct seeding and seedling planting. Information on direct seeding is applicable for bottomlands in the southern and southeastern United States. Information on seedling planting is divided into upland and bottomland sites.

In developing a historical perspective of planting and seeding oaks I selected 1970 as the reference year. A review article by Russell (1971) described the state-of-the-art of artificial regeneration and offered suggestions on research to enhance the success of this regeneration technique. I have summarized the article by Russell and have used it as a benchmark to see how far the science has advanced since 1970.

Russell (1971) concluded "that upland oaks could be established by seeding or planting, but additional experience was needed before these methods became economical alternatives to natural regeneration." Based on his research and the literature, he concluded the following: (1) Recently forested sites were generally more favorable for artificial regeneration than abandoned fields. (2) Lack of repellents to protect acorns from animals severely limited direct seeding, but oaks could be planted readily by conventional methods and would survive well on suitable sites. (3) Ample sunlight was required for the best growth of seedlings, and competing vegetation must be controlled. (4) At best, height growth was discouragingly slow. (5) Advances in cultural methods and the development of genetically improved stock were essential to make artificial regeneration practical.

While the greatest obstacle in direct seeding was the "lack of economical ways to protect acorns from animals," the limitation to planting was the slow initial growth of the seedling. Russell offered some possibilities for speeding growth:

1. Improved planting stock
2. Better methods for competition control
3. Fertilization
4. Genetic improvement

There has been an explosion of research dealing with artificial regeneration of oak species via direct seeding and/or seedling planting since 1971. Some of the accomplishments made since 1971 follow.

DIRECT SEEDING—BOTTOMLANDS

Johnson and Krinard (1985, 1987) reported that direct seeding of acorns may be a viable artificial regeneration method. They evaluated *Quercus falcata* var. *pagodifolia, Q. nigra, Q. nuttallii,* and *Q. shumardii* for their ability to germinate, grow, and survive in an abandoned agriculture field setting in the Mississippi delta and minor stream bottoms and in the silty uplands.

Advantages to sowing acorns as opposed to planting seedlings:

1. Less expensive (eliminates the cost of growing, transporting, storing, and planting the seedling).
2. Less time consuming than seedling planting.
3. Sowing is not seasonally dependent, though the best sowing is March-April 15 to minimize rodent depredation.

While results of direct seeding of oaks have been mixed, the successes have yielded the following:

1. Acorns must be covered with soil.
2. Fall and spring seeding are equally successful.
3. Animals, particularly squirrels and chipmunks, forage for and destroy and/or consume a high percentage of the seeded acorns. No suitable repellent was available.

Animal Damage

The earliest seeding tests conducted at the Forest Service Laboratory at Stoneville, Mississippi, were performed under a full forest canopy and were unsuccessful due principally to rodent damage. The researchers later discovered that seeding tests in site prepared forest openings of 2 acres or more in size or on agricultural fields had much less rodent damage. Research results and recommendations were based on seeding these types of sites.

Species

Research trials included Nuttall (*Q. nuttallii* Palmer), Shumard (*Q. shumardii* Buckl.), cherrybark (*Q. falcata* var. *pagodifolia* Ell.) and water (*Q. nigra* L.) oaks. Commercial plantings have included the above species as well as swamp chestnut (*Q. michauxii* Nutt.), chinkapin (*Q. muehlenbergii* Engelm.), overcup (*Q. lyrata* Walt.), willow (*Q. phellos* L.) and bur (*Q. macrocarpa* Michx.) oaks. Nuttall oak was the most adaptable species tested and consistently had superior percentage germination and growth over a wide range in sites from flood plains to silty upland sites. As a group, white oak (swamp chestnut, chinkapin, overcup, and bur) have lower percent seed germination in the field than the red oak group. Four seedlings per 50 ft. of linear row is considered adequate stocking.

Site Selection

The same guidelines used for evaluating sites prior to planting seedlings can be used for direct seeding (Baker and Broadfoot 1979). The major consideration is the timing and duration of flooding. The influence of these factors is species specific. For example, Shumard and cherrybark oak acorns should be planted on well-drained soils that flood only for short periods (a week or less) during the growing season. Neither species should be planted in clay soils subject to flooding during the growing season. Nuttall oak acorns, on the other hand, grow well in clay soils and can tolerate flooding during the dormant and early growing season. Water oak acorns are less tolerant of flooding.

Seed Collection and Storage

A key to successful artificial regeneration is the proper collection and storage of acorns. This important topic is covered in detail by Bonner in these Proceedings.

Time of Seeding

The percentage of seeds which germinate (seedling percentage) varies with the time of year the seeds are planted, but generally acceptable germination is attainable regardless of the time of year the seeds are sown. This finding is important because sites that are inundated with water or otherwise unworkable during the dormant season can be planted during the growing season after the water recedes.

Johnson and Krinard (1985) observed that acorns may remain dormant in the soil during the dry summer months and germinate when soil moisture is favorable, i.e., late in the growing season.

Depth of Seeding

Regardless of species and hence acorn size, seedling emergence is attainable with seed planted to a depth of 6 in. However, planting depth and seed size will influence percent germination and early seedling size (Johnson and Krinard 1985). The greatest seedling percentage occurred for seed planted at the 2-in. depth. Johnson and Krinard (1985) offered two reasons for sowing deeper than 2 in.: (1) to discourage pilfering by rodents and (2) to reduce the variability of the soil environment, i.e., temperature and moisture fluctuations. The first-year seedling heights were inversely related to planting depths. Site preparation, for seedbed preparation and weed control, is important to enhance seedling percentage and subsequent seedling survival and growth.

Method of Sowing

Both machine and hand planting have been successful. Hand planting is suited for cutover areas, rocky sites, or sites on steep slopes. Hand seeding has been improved by a tool developed by the USDA Forest Service Laboratory at Stoneville. Machine planting is best suited for open fields. Machines can accommodate a range in the size of acorns and will plant at various spacings. Machine seeding is an option only when soil moisture conditions are suitable.

Spacing

Johnson and Krinard (1985) reported that approximately 35 percent of planted oak seed germinate, that approximately 10 percent of the planted acorns produce a "free-to-grow-tree" in 10 years on cleared forested sites, and that 25 percent of the planted acorns produce "free-to-grow-trees" on old field sites. Therefore, sowing 1,500 acorns per acre would produce 500 seedlings the first year with 150-375 "free-to-grow-trees" in 10 years. Between- and within-row spacing should allow for approximately 30 sq. ft. per acorn (Johnson and Krinard 1985).

Survival and Growth

Growth rates differ by species and site but, in general, survival is generally good but growth is slow for the first 5 years with only 1 to 2 ft. of height growth for the best seedlings. From age 5 to 15, trees may average 2 to 3 ft. of annual height growth. Correspondingly, diameter growth is also slow for the first 5 years and more rapid from years 5 to 15 (Johnson and Krinard 1985).

Case Studies

Johnson (1983) reported on an 11-year-old study in which Nuttall oak was direct seeded in April either by machine or manually at 2-, 4- or 6-in. depths in a 20-acre, intensively site-prepared clearing (double disked) in the Mississippi delta. Field germination averaged 36 percent and was not influenced by method or depth of sowing. After 11 years, two-thirds of the Nuttall oaks (551 per acre) were free to grow and averaged 2.1 in. in diameter and 17 ft. in height.

Francis and Johnson (1985) reported that direct-seeded sawtooth oak (*Q. acutissima* Carsuth.) grew well on the Mississippi flood plain despite high soil pH, short-term flooding, and poor soil aeration. Sites were cleared and disked before seeding in April. Approximately 60 percent of the sown seed germinated and survived. Trees averaged 31 ft. in height and 4.6 in. in diameter after 14 years.

Johnson (1984) reported on the 10-year results of cherrybark and Shumard oak direct-seeded in the silty uplands near Vicksburg, Mississippi. The 3-acre openings were created by cutting and removing all trees >1.0 in. d.b.h. The field germination of winter-sown acorns was 42 percent for cherrybark and 55 percent for Shumard, about twice that of spring-sown acorns. After 10 years, the average height of codominant trees averaged 23.6 ft. for Shumard and 27.0 ft. for cherrybark. The average d.b.h. was 1.5 in. for both species. The dominants and codominants in the competing natural stand averaged 40 ft. in height and 3.5 in. d.b.h. Only 5 percent of the seed spots had oak in a free-to-grow position; most codominant oaks were on higher, drier sites where competition was less severe. Johnson (1984) concluded that "direct seeding to supplement stocking of natural oak has merit in spite of severe competition from natural regeneration."

SEEDLING PLANTING —UPLANDS

If hardwoods are to be planted in clearcuts, Johnson and Rogers (1982) recommended planting in the spring after harvest cutting to take advantage of favorable soil moisture and light conditions.

Site Preparation

Johnson and Rogers (1982) recommended the application of herbicides to increase planting success. Herbicides can be selected to control specific types/groups of vegetation (annual weeds, perennial grass and broadleaf species, and woody plants). The science of vegetation management has advanced since 1982 when Princep 80W[1], Tordon 101R[1] and Roundup[1] were the foundation of weed control in forestry. Products have become more species specific, have greater efficacy, and are more environmentally safe. Application technology minimizes drift to nontarget plants and is more effective at treating target plants with a minimal amount of chemical to be effective. "Although the effectiveness of one herbicide application in reducing competition is likely to be temporary, the impact on planted trees, especially slow-growing species like the oaks, may nevertheless be significant" (Johnson and Rogers 1982). Once established, oaks can become successful competitors.

Number of Trees To Be Planted

Results from West Virginia (Wendel 1980) indicate that after 7 years, 30 to 50 percent of the 2+0 red oak seedlings planted in a clearcut were judged successful. This result suggests that 2 to 3.3 red oaks should be planted to obtain one successful tree. This success ratio may be influenced by site, climate, competing vegetation, and quality of the planting stock.

Underplanting

Underplanting allows the root system of the planted trees to become well established before competition peaks after clearcutting. To be successful, both overstory and understory density control may be required to produce the light and soil moisture conditions necessary for adequate development of planted trees before the final harvest.

Johnson (1984) measured survival and height growth of northern red oak underplanted in the fall in mature stands and also planted in clearcuts. The overstory was removed between the third and fourth growing season. Among the underplanted trees, the 1+1 clipped seedlings grew the fastest. The greater growth for the clipped seedlings in the underplanting could be related to a more favorable root:shoot ratio.

The optimum length of time between planting and overstory removal is uncertain. Johnson speculated that, over long periods, mortality of underplanted trees would outweigh the growth advantage underplanting might provide and that a 2-3 year period would provide underplanted oak the time needed to increase its growth potential.

Tworkoski, Smith, and Parrish (1986) reported on seedling survival and growth of red and white oak underplantings in the Virginia Piedmont. Seedlings were underplanted followed by no canopy removal, partial removal (shelterwood), and

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[1] Mention of trade names does not constitute endorsement of the product by the Department of Forestry and Natural Resources, Purdue University.

total removal (clearcutting). Seedling survival was high (90 percent). Growth increased with the degree of canopy removal.

Myers and others (1989) evaluated six types of northern red oak nursery stock planted in the understory of a mature stand of upland hardwoods in southern Indiana after 6 years. Overstory removal consisted of thinning from below to 60 percent stocking or a control. While thinning and understory control treatments resulted in the best survival (64 percent) and height growth (78 cm) it was not significantly different from the understory control treatment, i.e., understory control is important to the success of underplanted seedlings. Treatment differences associated with nursery stock type were nullified because of severe deer browsing.

Quality of Nursery Stock

Johnson (1979) reported that 1+1 red oak transplants performed better than 1+0 seedlings even when the 1+0 seedlings were larger. Johnson suggested that undercutting seedlings in the nursery bed might result in the same advantages as observed with 1+1 transplants. The minimum size standard for northern red oak in the Lake States is: 50 cm (20 in.) height and 8mm (5/16 in.) caliper.

Stroempl (1985) described grading standards for northern red oak seedlings to be used in field plantings in southern Ontario. The grading criteria were based on root-collar diameter and stem length and stem form, bud number, and roots of large and small 2-0 nursery stock.

Seedling size	Root-collar diameter (mm)	Stem length (cm)
Large	7.5-8.5	55-75
Small	4.5-6.5	30-45
Cull	<4.5	------

Stem form. The stem should be well defined and straight, with relatively short branches on the previous year's growth. Long branches should be pruned and multiple leading shoots pruned to leave the sturdiest shoot on seedlings that have met all other criteria. Seedlings with multiple stems should be culled and the sources of acorns that do poorly identified and eliminated as a seed source.

Buds. The stem should have numerous buds, especially on the last year's growth, and a cluster of buds at the apex. Buds should not be swollen or flushed at the time of planting.

Roots. The "hockey stick" root which results from undercutting may make it more susceptible to root rot and may not properly support the developing crown. Root should be pruned to about 20-25 cm to facilitate field planting and ensure a high rate of survival.

Seed Source. Acorns should be collected from local sources and screened to select for adaptability and rapid juvenile growth.

Physiological Quality of Nursery Stock

Appropriate sized nursery stock has the potential for rapid root and shoot growth (Farmer 1975b, Johnson 1979) but this growth potential is often not realized because of the poor physiological condition of the seedling. The physiological condition of nursery stock at planting is greatly influenced by the dormancy environment that immediately precedes planting.

Fall- and winter-lifted stock requires the proper storage or the physiological quality may decline. Seedlings should be kept cool (1-5 °C) and moist. The practice of heeling-in seedlings as a storage method is no longer recommended because of the inability to control root temperature and moisture conditions and the increased likelihood of the development of root diseases.

Spring-lifted seedlings and heeled-in seedlings are subject to desiccation resulting in shoot dieback. Because both shoot dieback and frost heaving may occur in fall-planted bareroot seedlings, Johnson (1979) recommends spring planting.

In oak, the winter shoot dieback is associated with reduced and delayed root growth capacity and reduced shoot growth (Johnson 1979). The cause of winter shoot dieback is linked to bud viability rather than the shoot, *per se*.

Buds play a major role in the initiation of root growth in oaks. Johnson and Rogers (1982) stressed the need to protect buds of dormant oak seedlings against both physiological and physical damage during lifting, handling, and storage. It is also important to plant trees as soon as possible after receiving them from the nursery and to do so with proper field handling and planting techniques (Johnson and Rogers 1982).

In 1971 Russell determined that root pruning and top clipping did not reduce the survival and growth of 1-0 northern red oak planted in bar-slits when compared to "ordinary nursery stock planted in the center-hole method."

Seedlings were root pruned to 5 in. and top clipped to 5 in. above the ground line. Ordinary seedlings had tap roots averaging 11 in. Toliver and others (1980) reported that after 5 years the combination of top pruning and root pruning of water oak and willow oak resulted in the best height growth, when compared to other combinations of pruning or no pruning and averaged 332 and 372 cm, respectively. Survival was 82 percent for water and 90 percent for willow oak.

The root system is believed to be the key to the above ground growth of planted seedlings (Farmer 1975a). Seedlings should have a favorable root:shoot ratio, and an abundance of first-order lateral roots, which are capable of developing new roots. Barden and Bowersox (1989) experimented with pre-sowing radicle root clipping and lateral root pruning in the nursery. When compared to the control, the combination of root treatments resulted in a doubling of the root growth capacity and larger diameter seedlings with greater leaf area.

Ruehle and Kormanik (1986) and Johnson (1989) have demonstrated that the persistent first-order lateral roots, stem height and diameter, and seedling vigor are important factors for the successful establishment of planted oak seedlings. Methods to produce high-quality seedlings in the nursery have been presented by Johnson (1988) and Crow and Isebrands (1986).

Ruehle and Kormanik (1986) stated that for oak seedling planting to be successful it was important "to identify at lifting time the individual seedlings that will develop an extensive root system after planting and grow well in height during the next 5 years." Gall and Taft (1973) and Webb (1969) cautioned on making early comparisons between seedlings since rankings often change after planting. More recently, Kormanik and others (1989) evaluated the frequency distribution of lateral roots of 1-0 bareroot white oak seedlings and correlated measurements of above-ground seedling growth in the nursery with lateral root development. Approximately 24 percent of the seedlings had 11 or more first-order lateral roots and offer the best chance for outplanting success (Kormanik and others, 1989). Evidence suggests that large oak seedlings with five or more lateral roots offer the potential for rapid growth (Schultz, personal communication). Others have not found this direct relationship (Kaczmarek 1991, Kaczmarek and Pope 1992).

The selection of genotypes with a high probability for rapid growth is still elusive. Maybe the phenotypic expression of the root system is a key. Techniques in DNA mapping and micropropagation provide new tools to identify and propagate superior genotypes.

Buchschacher and others (1991) recommended that oak seedling quality would be improved by using seed collected from superior trees or stands (registered for collection) rather than purchased from unrestricted public collections. Sowing beds by seed source and undercutting should decrease within nursery bed seedling variability and increase seedling quality and outplanting success.

Planting Prescription

Johnson and others (1986) presented a four-step prescription for underplanting northern red oak in the Missouri Ozarks: (1) Control undesirable woody understory vegetation with herbicides before planting. (2) Create a medium density shelterwood. (3) Underplant large-diameter nursery stock (at least ½ in. diameter 1 in. above root collar) with clipped tops. (4) Remove the shelterwood three growing seasons after planting. Johnson and others stated that this prescription would result in the successful establishment of ⅓ to ½ of the planted trees 2 years after the shelterwood is removed.

On the average, shoot growth for planted upland oak seedlings is less than 10 cm per year. Typically, shoot growth of planted seedlings is restricted to the early part of the growing season when soil moisture is readily available. Weed control, including mulches, has generally not significantly improved oak seedling growth on forest sites (Wendel 1980, Hilt 1977). Fertilization has improved growth in some instances (Johnson 1980) but gains generally have not been large enough to justify the added cost. Approximately 10 percent of northern red oaks planted in forests grow 50 to 60 cm per year (Johnson 1976, Wendel 1980) which compares favorably to that of dominant natural reproduction in clearcuts on site indexes from 60 to 70.

Fall planting as a means of establishing seedlings prior to the spring growth period has been tried off and on for decades, always with mixed success. Johnson and Rogers (1982) reported that fall-planted container-grown seedlings had greater shoot growth and minimal shoot dieback when compared to 1-1 transplants and 1-0 seedlings respectively. In all cases the height growth of fall-planted seedlings exceeded that of spring-planted seedlings after 1 year. The minimal shoot dieback is particularly significant because gains made in shoot elongation are often negated by shoot dieback.

Containerized Seedlings

In 1978 only a small percentage of the more than 100 million container-grown seedlings produced were hardwoods. Container stock as large as a comparable bareroot seedling may cost four times as much; smaller container-grown seedlings may be as low in cost as bareroot seedlings (Tinus 1979).

Container stock costs more to transport and handle but the actual planting was easier and cheaper in some cases, i.e., when an automated tree-planting machine was used (developed by USDA Forest Service, San Dimas Equipment Development Center, J. L. Edwards). Hand-planting tools, which reduce planting effort and increase the planting rate by two to three times, have been developed for planting container-grown seedlings.

Container grown oak can be produced rapidly and survives well in the field (Tinus 1979). Container stock should be used on harsh sites, including south-facing slopes and sandy upland soils throughout the United States. Planting is most successful when the stock is dormant but ready to grow new roots. The keys to field performance are proper physiological condition, the right balance between shoot and root, and adequate size (Tinus 1979). The tree planter must have the proper equipment and must be motivated and know how to do a good planting job. Tinus (1979) concluded that it is the cost of the established seedling "free to grow" that counts, not the cost of the seedling at the nursery.

Mycorrhizae and Oak Regeneration

Marx (1979) introduced the idea of using specific mycorrhizal-forming fungi to improve the growth and physiological condition of oak seedlings produced in the nursery and in containers. Marx projected the superior growth of these oak seedlings in field plantings. Based on his experience with loblolly pine (*Pinus taeda* L.), he was able to create an inoculation system that was successful in producing mycorrhizae on white oak (Marx 1979a) and red oak (Marx 1979b) seedling roots grown in the nursery. Other researchers (Dixon and others 1980, 1981; Garrett and others 1979) reported similar successes with black oak and northern red oak (Pope 1988, Dixon 1989). In all cases seedlings inoculated with the fungal species *Pisolithus tinctorius* were larger and had more root mass than control seedlings and those colonized by indigenous fungi. Similarly, fungal inoculations have been successful in forming mycorrhizae on a variety of oak species in container systems (Maronek and Hendrix 1979, Maronek and others 1981, Pope and Chaney 1985, Beckjord and others 1986, Kissee and others 1989, Reber 1991).

While fungal inoculation results in the formation of mycorrhizae and subsequent growth simulation of oak seedlings under control conditions, these same mycorrhizal seedlings rarely show any survival and growth advantages over control seedlings in field plantings. The early growth advantages of seedlings inoculated with mycorrhizal-forming fungi are often eclipsed by "non-inoculated" seedlings within 2 to 4 years after outplanting except on nutrient deficient and/or drought stressed sites (Beckjord and McIntosh 1983).

Tree Shelters

Tree shelters are reported to increase height growth of planted 2-0 northern red oak (Lantagne and others 1990, 1991). Red oak seedlings planted in southern Michigan and grown in shelters were 53 cm taller than unsheltered trees after 3 years. The height growth of sheltered seedlings was related to the increased extension of the initial growth flush without substantial increases in stem caliper and dry weight. This growth pattern is the major concern expressed for not using this technology. In Great Britain, however, the use of two shelters increased from 80 in 1979 to more than 6 million in 1986 (Potter 1987).

Case Studies

Johnson (1980) described the 8-year growth response of five oak species planted in the Missouri Ozarks to fertilization with magnesium ammonium phosphate (8-40-0), a slow release amendment. The fertilizer was applied at the time of planting at a rate of 100 pounds of nitrogen and 500 pounds of phosphorus per acre. Fertilization increased height growth for black oak and scarlet oak but did not affect northern red oak, white oak, and post oak. Fertilization improved the survival of all species but black oak. In addition to an increase in mean height, fertilization increased the percentage of seedlings in the 6-, 8-, and 10-ft. height groups for black and scarlet oak and in the 10-ft. group for white oak. Competition control is essential to realize the growth potential from fertilizer applications (Johnson 1980).

Based on the results of two long-term studies, McGee and Loftis (1986) concluded that planting oak on upland sites in North Carolina and Tennessee using conventional methods does not offer a solution to oak regeneration problems. In one study, 1-0 northern red oak seedlings were separated into three classes based on root collar diameter and planted in six clearcuts. Competing vegetation was controlled prior to planting and for 5 years thereafter. The site index for northern red oak was 75 to 98 (base age 50). Survival of the largest grade seedlings was slightly greater than grades 2 and 3, but height growth was the same. Survival averaged 88 percent after 5 years but declined rapidly after the cleanings stopped. By age 19, survival was 6 percent, height averaged 17.9 ft., and the free-to-grow percentage averaged 0.6.

In another study located in the Cumberland Plateau (ridges and hollows) and Highland Rim (barrens and fragipans) of Tennessee, black oak seedlings were planted in clearcuts which had been chemically treated to control competing vegetation. Cleaning treatments were initiated when the planted trees were either 6, 7, or 8 years of age. Except for the Plateau hollows, cleanings had little beneficial effect on survival or height growth. Overall survival averaged 88 percent for five annual cleanings and 81 percent for uncleaned areas. Height after 12-14 years average 1.7 to 8.5 ft. and was related to site quality. Height growth of yellow poplar (*Liriodendron tulipifera* L.) planted in companion plots and not cleaned averaged 1.6 to 3.9 ft. per year.

McGee and Loftis (1986) concluded that, given the good early survival, planting could become a viable regeneration alternative for red and black oak if techniques could be developed to accelerate height growth.

Red oak seedlings (1-0 stock) were planted in an upland oak-hickory forest thinned to 60 percent stocking (Gingrich 1967). The competition was chemically treated prior to planting. Seedling survival was highest when the understory was controlled, but height growth was not affected. Deer browse was identified as a serious problem in this study and may have influenced the results in height growth (Myers and others 1989).

SEEDLING PLANTING —BOTTOMLANDS

Bottomland oak species are not satisfactorily regenerated after the harvest because small seedlings are not able to compete successfully with undesirable stump and root sprouts and/or faster growing seedlings (Johnson 1979, Johnson and Krinard 1976). Some regeneration problems can be solved with artificial regeneration. Survival is often good but slow initial growth requires intensive control of competing vegetation, usually by cultivation, if planted seedlings are to develop rapidly and compete.

Seedling Morphology

Research in artificial regeneration has focused on improving the early growth of outplanted seedlings. Early field performance was influenced by nursery practices and container production. Seedlings of acceptable size (2-½ to 3 ft. in height; ⅜+ in. root collar diameter) and vigor can be produced in the nursery in 1 year, provided that the nursery bed density is 10 seedlings per sq. ft. or less and the seeds are sown early enough in the spring (Hodges and Janzen 1987). Hodges and Janzen (1987) reported that undercutting and lateral root pruning increased root proliferation, but these results had no effect on height growth of outplanted seedlings.

Moorhead (1978, 1981) reported that containerized seedlings of bottomland red oaks had greater initial height growth after outplanting than nursery grown bareroot seedlings of the same age. The growth difference was not great enough to eliminate the need for competition control. The additional cost of growing containerized seedlings could not be justified in this study. Enrichment planting will require competition control in the lower canopy to successfully augment natural regeneration (Chambers and others 1987, Nix and Cox 1987). By 1986 research at the USDA Forest Service Laboratory at Stoneville had shown repeatedly that certain bottomland oaks can be successfully established via planting 1- to 3-year-old seedlings and controlling weeds.

Site Preparation

Nix and Cox (1987) showed that preharvest competition control enhanced the probability of successful enrichment plantings with cherrybark oak. They evaluated overstory removal (clearcut and shelterwood) in combination with preharvest disking and post-planting, directed herbicide application. Disking increased survival and growth of seedlings planted in clearcuts. Similar results were evident in the shelterwood, but harvesting damage eliminated any preharvest disking treatment effect.

Nix (1989) evaluated the effect of mulching, and spring or fall application of herbicide on the survival and growth of 1-year-old cherrybark oak seedlings planted in a clearcut. Site preparation was done after clearcutting; no attempt was made to establish a cultivated plantation of oaks but rather to establish an enrichment planting. After six growing seasons, survival was greatest for the herbicide treatments (95 percent) followed by the mulch treatment (88 percent) and the control (75 percent). Treatments did not significantly affect height, or basal diameter, but all were significantly greater than the control. Spring herbicide treatment gave superior results.

Miller and Burkhardt (1987) tested herbicides and methods of application in enrichment plantings of cherrybark oak. The trials were conducted on the loessial bluff forests in western Mississippi. The test included injection of overtopping trees and soil-active pelleted herbicides. After 3 years, the treatment of soil-active herbicide yielded seedling volumes significantly greater than those on the untreated plots.

Seifert and others (1985) evaluated the 5-year response of 1-0 swamp chestnut oak seedlings planted on a poorly drained upland flat in southeastern Indiana. Site preparation included disking and disking plus bedding. Chemical weed control was applied annually in the spring around all seedlings. Survival averaged 83 percent and was unaffected by treatment. Mean seedling height was greatest for the disked treatment. Fifty-two percent of the seedlings in the disked and 45 percent in the disked plus bedding treatments were greater than the overall mean seedling height, as compared to 16 percent for the control. Mechanical site preparation may be important for establishing oaks on poorly aerated loessial flats.

Plantation Management Plan

Based on 10 years of research, Malac and Heeren (1979) provided a plantation management plan for willow, water, and laurel oak in the southeastern United States. No speculation was made on the cost of implementing such a plan:

1. Seed should be collected from the best available local trees.
2. Sites selected for planting should have a sandy loam or loam surface fairly high in organic matter, and should have a water table within 4 in. of the surface during portions of the year.
3. Plant only large, healthy seedlings, with a minimum root collar diameter of ⅜ in. and a top height of at least 2 ft.
4. All sites should be intensively cleared, except for recently abandoned agricultural land. Some sites should be disked prior to planting, abandoned fields with plow pans or shallow topsoil should be subsoiled, and wet sites bedded.
5. Seedlings should be planted by a machine which has been modified to accommodate large seedlings.
6. Depending on site and weed growth, plantations should be disked two to three times a year for at least the first 2 years.
7. Fertilizer should be applied during the first cultivation; applications vary, but a general recommendation is 250 lb./acre triple superphosphate or diammonium phosphate.

CONCLUSIONS

Regeneration of oaks by planting or direct seeding remains very uncertain. There are no foolproof methods or techniques that can guarantee success. The process, from seed collection to planting (seed or seedling) to young plantation management, is rife with pitfalls. The vagaries in weather, site conditions, and impacts of animals, insects, and disease all add to the uncertainty. Given all the potential problems, it is encouraging that successful artificial regeneration of oaks is occurring more frequently. The science/art of artificial regeneration has made significant advancements since 1971.

Research in direct seeding has provided methods that reduce animal predation of acorns and has identified oak species which are adaptable to a range of soil and site conditions. Research has led to better site selection for direct seeding and has described needed site preparation. For some oak species, information is available on season (time of year) and methods of sowing and spacing to achieve desired stocking levels. Research on seed collection and storage provides the knowledge to ensure that, at planting, the seeds are sound, robust, and physiologically capable of expressing their growth potential.

Research in seedling production has explored use of mycorrhizal fungal symbionts to enhance seedling growth, root growth potential, plant water relations, and the physiological condition of the seedling. Growing oak seedlings in containers is possible, and using container-grown seedlings has merit on stressful sites. Root systems colonized with specific mycorrhizal fungi and/or container-grown seedlings have not proved to have the widespread advantages once proposed for oak regeneration.

Research efforts have focused on identifying the seedling characteristics that are associated with survival and adequate growth and creating favorable site conditions. Efforts have centered on root morphology, developing an adequate number of lateral roots, creating the proper top:root ratio, and producing a physiologically superior seedling. Similarly, research has investigated the impacts on site (site preparation and weed control) and canopy manipulations (clearcutting, shelterwood, thinnings) on oak seedling survival and growth. Great strides have been made in these areas, but the large within-species and within-family genetic variability have resulted in non-uniformity of response to management treatments.

Even with all the uncertainties inherent in the procedure, artificial regeneration offers the best solutions to many oak regeneration problems in the future. Clearly, continued failures of natural regeneration make it imperative to press forward for breakthroughs in genetics, economics, and the biology of early growth. Today, land managers should proceed with the planting and seeding of oaks, but they should consider all the information provided in this symposium and proceed with caution.

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Artificial Regeneration of Bottomland Oaks

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ABSTRACT

Research results from the Southern Hardwoods Laboratory, Stoneville, Mississippi, on direct-seeding and planting oaks is now being applied to establish commercial plantings. The Louisiana Department of Wildlife and Fisheries has successfully planted and direct-seeded over 4,000 acres during a 5-year period. Primary species were Nuttall, water, willow, and Shumard oaks. The Mississippi Department of Wildlife Conservation is well into a 10-year program of direct-seeding oaks on the Malmaison Game Management Area. Large-scale plantings (seedlings) and direct-seeding of oaks are being conducted under the Conservation Reserve Program in Louisiana, Arkansas, Mississippi, Tennessee, and Alabama.

Over 10 years, the growth and development of saplings of four oak species planted at five spacings in a minor stream bottom in southeast Arkansas showed significant differences among species and spacings. Spacing affected all tree-size and biomass variables but had no effect on survival. Water oak developed most rapidly; swamp chestnut oak most slowly.

Measurements made on a 27-year-old water oak plantation near Winnsboro, Louisiana, and a 20-year-old cherrybark oak plantation near Vicksburg, Mississippi, showed that oaks can be successfully grown in plantations.

Successful plantings from direct-seeded Nuttall, water, cherrybark, and Shumard oaks have been established.

The importance of site-species selection, site productivity, soil water, effects of flooding depth and duration, and site preparation is emphasized. Basics of planting and direct-seeding, including seedling and acorn quality, spacing, storage and handling, and hand versus machine planting and direct-seeding, are discussed.

INTRODUCTION

Bottomland hardwood forests provide sites for some of the most productive timber and wildlife habitat in the United States. Additional benefits are improved water quality from forests that act as filter zones along streams and restoration of deteriorated sites. Such sites support two to five times as many game animals as do upland pine sites. Hard-masted species, such as oak and pecans, provide extremely important resources for wildlife. Deer, turkey, rabbits, squirrels, migratory ducks, and wood ducks are taken in great numbers each year from hardwood forests (Allen and Kennedy 1989).

Before the first European settlers arrived on the North American continent, dense hardwood forests and cypress-tupelo forests covered the floodplains of major and minor stream bottoms, mountainous coves, and the swamps along coastal areas. More than 100 species were represented (Freeman and Frome 1968). The tremendous agricultural potential of the areas with their rich soils and abundant moisture, especially those along rivers and streams, was realized almost immediately. Gradually, as flooding was brought under control and drainage projects were established, increasingly more hardwood forests were cleared for agriculture.

By the late 1930's, about half the original eastern hardwood forest had been cleared. Bottomland clearing continued at a rapid pace through the late 1970's, especially in the lower Mississippi River Valley. It is now apparent that many areas that were cleared would be better suited as forests because they are subject to flooding and can successfully produce an agricultural crop only in relatively dry years (Allen and Kennedy 1989). These areas, and many other forests where an oak component is not present, can only be reforested to oaks by using artificial regeneration. Artificial regeneration of bottomland oaks can be accomplished in the South using direct-seeding or planting methods developed at the Southern Hardwoods Laboratory in Stoneville, Mississippi. Landowners who wish to reforest oaks artificially must make several decisions that reflect a high level of commitment to meeting requirements.

PLANNING AN ARTIFICIAL REGENERATION PROJECT

Careful planning is the first and most critical step in a regeneration project (Allen and Kennedy 1989). Landowners must decide on location and site preparation needs for the planting or direct-seeding site, tree species, quantity of seedlings or seeds needed to complete the project, and the mode of planting or seeding. These decisions must be made well in advance of the planting or direct-seeding date (preferably as much as a year) to ensure availability of planting or seeding stock, labor, and equipment.

Proper tree species selection greatly affects the probability of success of the project. Selection must be based on factors such as soil type, frequency and duration of flooding (table 1), flooding depth, site-species adaptability, availability of planting stock, and objectives for regeneration. In many planting projects in the lower Mississippi Valley, emphasis has been placed on hard mast-producing species such as oaks (*Quercus* spp.) and sweet pecan (*Carya illinoensis* (Wangenh.) K. Koch), for both timber production and wildlife. Light-seeded species such as sweetgum (*Liquidambar styraciflua* L.), sycamore (*Platanus occidentalis* L.), and the ashes (*Fraxinus* spp.) usually become established on the site because their seeds are easily dispersed by wind and water. Planting technology for other hardwoods has also been developed.

The two major reforestation methods are direct-seeding and planting seedlings, both of which can be done by hand or machine. Planting includes 1-0 seedlings and older, larger seedlings where fewer seedlings per acre are planted as enrichment or supplemental plantings. Two large, well-planned seeding and planting programs are those of the Louisiana Department of Wildlife and Fisheries and the Corps of

Table 1—Species tolerance in relation to flooding time and duration

- Continuous flooding -		- - - - - Periodic flooding - - - - -		
January-June	**January-May**	**January-May**	**January-April**	**January-March**
Cypress	Green ash	Sweetgum	Sawtooth oak	Shumard oak
Overcup oak	Nuttall oak	Water oak	Sycamore	Cherrybark oak
Water hickory	Persimmon	Willow oak	Cottonwood	Swamp chestnut oak
		Nuttall oak	Sweet pecan	Nuttall oak
		Green ash	Nuttall oak	Green ash
			Green ash	

Engineers Lake George project. The Louisiana group has direct-seeded and planted over 4,000 acres during a 5-year period in old fields in the Ouachita Wildlife Management Area near Monroe, Louisiana. The Lake George project is an 8,800-acre area in west-central Mississippi that will be planted and direct-seeded over a 5-year period. Direct-seeding oaks is usually less expensive than planting oak seedlings, but costs depend on species, seed price, labor, availability of seedlings, and other factors. Direct-seeding costs per acre on old fields are estimated at about 40 percent those of planting seedlings (Bullard and others 1992). Also, direct-seeding has been successful only with hard-mast species such as oaks, pecan, and hickories (*Carya* spp.) (Johnson and Krinard 1987). Bare-root seedlings would have to be planted for the light-seeded species. Planted oak seedlings have faster establishment and growth rates through the first several years (Allen 1990, Wittwer 1991).

SITE PREPARATION

Site preparation may be necessary to create suitable growing conditions or to facilitate the use of mechanical planters or seeders. If the area has been in cultivation for a long time, site preparation should break up any plow pan or otherwise compacted soil and aid in weed control during the growing season after planting. Disking with a heavy disk at least twice late in the summer before planting is recommended. Disking should be to at least a 6-in. depth and preferably 8 to 15 in.

SITE-SPECIES SELECTION

Growth of bottomland hardwoods depends on the physical condition of the soil, moisture availability during the growing season, nutrient availability, and aeration (Baker and Broadfoot 1979). Bottomland oaks grow best on moist, well-drained sites with good fertility and medium-textured soils. They will grow on the finer textured clays, but survival will probably be lower and growth will be slower. Growth is best in pH ranges of 6.0 to 7.0, but good survival and growth have been obtained with oaks in pH ranges as low as 5.0 to 5.4 (Kennedy 1985, Kennedy and others 1987). Soil pH above 7.5 limits growth and survival of several red oak species, although Shumard oak (*Q. shumardii* Buckl.) grows well at these high pH ranges (Kennedy 1984, Kennedy and Krinard 1985).

County soil surveys contain a wealth of information on soil characteristics (including degree of flooding and soil saturation) that affect the survival and growth of trees, as well as information on the suitability of the soil type(s) on the site for various tree species (Allen and Kennedy 1989).

Another good source of information is local expertise. Nearby landowners may know of changes in flooding patterns (due to drainage, etc.) that are not covered in the soil survey. They may also know of other planting or direct-seeding projects in the area and can relate any problems that were encountered.

DIRECT-SEEDING

Oak seeding research at the Southern Hardwoods Laboratory was begun in the early 1960's. Direct-seeding is becoming a widely used method of reforestation, particularly in the lower Mississippi River Valley. Since 1981, some 5,000 to 10,000 acres of publicly and privately owned land have been direct-seeded with acorns or other heavy mast species.

Many early tests were with Nuttall oak (*Q. nuttallii* Palmer). The slow growth of this species (and of most oaks) in the first 5 years may be discouraging because competing sprouts and seedlings of other species outgrow the oaks. However, within 10 to 15 years, enough oaks should be in a competitive crown position to ensure their presence in the future sawtimber stands (Johnson and Krinard 1987). Although Nuttall has been the most popular red oak to direct-seed and has the highest success rate, at least six other red oak species, four white oak species, and sweet pecan have been successfully direct-seeded (Johnson and Krinard 1987). Species selection should be based on site quality and landowner preference.

Guidelines for direct-seeding Nuttall oak also apply to other hard mast species; however, lower germination rates can be expected with other oaks and pecan. Because white oaks germinate in the fall and the acorns are hard to store, acorns should be direct-seeded as soon as possible after collection.

Collecting and Storing Seeds

Acorn collecting is the biggest job in a direct-seeding program. In the South, collections are normally done between October 1 and January 1. Fallen acorns are quickly eaten by birds, deer, and rodents and the time when acorns drop varies by species and individuals within a species, so one needs to keep checking the trees (Johnson and Krinard 1987).

Early seeding eliminates long-term storage that requires cold space and monitoring. Freshly collected acorns seem to be less attractive to rodents if they are seeded immediately; unlike acorns that have been in cold storage, they do not exude odors that attract rodents (Johnson and Krinard 1987).

Many oaks produce an excellent seed crop only 1 or 2 years out of every 5. Thus, for storable red oak acorns (Bonner 1973), extra collection may be required during good seed years. Storage may be expensive, but it is more reliable and productive than collecting acorns during poor crop years. It allows for an annual seeding program even in years of total acorn crop failure.

Practical time limits for storing large quantities of red oak acorns may be less than the 5 years, as indicated by research (Johnson and Krinard 1987). In Louisiana, about 5,300 lbs. of Nuttall oak acorns were collected during fall-winter 1984-85, stored in a walk-in cooler at 35 °F to 40 °F, and used during the 1985, 1986, and 1987 planting seasons (about 30 months of storage). However, if they are not properly stored, acorns can lose viability after 1 year. In the Louisiana study, the acorns were stored in polyethylene bags with about 20 to 25 lbs. of seed per bag. This made handling easier and kept seeds from heating in the bag (Johnson and Krinard 1987). The bags were placed in cold storage on shelves to allow for air circulation. If weevils were present in the acorns, they would emerge, eat through the bag, and fall to the floor from the wire shelves, thus minimizing damage to the bags.

Collecting. As a general rule, acorns of white oak cannot be stored more than 3 to 4 months because they normally germinate in the fall. Rink and Williams (1984) suggest that acorns of *Q. alba* L. be stored in 1.75-mil polyethylene bags instead of the 4-mil bags suggested for red oak acorns because of lower germination after storage in 4-mil bags. Suspected causes of lower germination were higher concentrations of ethanol and carbon dioxide.

Labeling. It is important to label storage bags to identify species, collection date, and percent soundness.

Seeding Operations

Water (*Q. nigra* L.), cherrybark (*Q. falcata* var. *pagodifolia* Ell.), Shumard, and Nuttall oak acorns can be removed from cold storage and sown with good results even in the early summer. The least desirable months for planting in the South and Southeast are July through October, when the soil is normally hot and dry (Johnson and Krinard 1987). Seeds that germinate in cold storage will produce seedlings when field-sown even if their radicles are broken off (Bonner 1982). Acorns of site-suitable species can be sown in flood areas soon after the water recedes—usually in April, May, or June—and should germinate and produce healthy seedlings.

Old fields have been hand- and machine-sown with and without site preparation, but seeding is easier and generally more successful on intensively prepared sites. Mechanical seeders cannot operate effectively in areas after a harvest cut because of the resulting slash and stumps.

Machines used for seeding are actually modified one- and two-row soybean seeders. Some drop acorns automatically; others are ridden by operators who drop acorns at specified distances. Seeders that drop seeds automatically should be checked at the end of each row to make sure the hopper does not jam, leaving long distances unseeded. Seeds sown 1 to 6 in. deep will germinate and produce seedlings. Seeding at greater depths slows germination and emergence of the young shoot; about 2 in. is the recommended depth. Reported direct-seeding rates range from 30 to 40 acres per day with a three-person crew using machines, to 6 to 8 acres per person with hand seeding. Normal spacing is rows 10 to 12 ft. apart and acorns 3 to 5 ft. apart within rows, or 1,000 to 1,500 acorns per acre. Research at the Southern Hardwoods Laboratory has shown a high rate of success when direct-seeding is done in complete openings greater than 100 ft. on a side. Direct-seedings in smaller openings have generally failed as a result of rodent damage (Johnson and Krinard 1987).

Germination as high as 80 percent has been reported in some research trials (Johnson and Krinard 1987). However, about 35-percent germination will be more typical for commercial sowings. Thus, 1,000 to 1,500 acorns per acre can be expected to produce 300 to 500 1-year-old trees, which would be a sufficient number for most objectives.

On the basis of limited data (Johnson and Krinard 1987, Bullard and others 1992), it appears that seedlings can be established 1 year after direct-seeding at a lower cost than planting seedlings. However, there are so many influencing factors that reliable cost comparisons would involve a thorough economic analysis.

Some situations may not be conducive to direct-seeding. Failures may occur under adverse field environments (such as free water coupled with high temperatures, a deadly environment for newly germinated acorns), extended periods of drought during the growing season, residual chemicals in old fields, presence of animals (especially raccoons), and defective acorns or improper storage techniques.

Post-Direct-Seeding Operations

Most land managers have not attempted to control weeds around direct-seeded oaks in old fields (Johnson and Krinard 1987). In some research trials, bushhogging between rows of seedlings appeared to improve seedling survival and growth. If one is willing to accept a little lower survival and growth, competition control may not be necessary in natural stand openings until free-to-grow oaks are 15- to 20-ft. tall (Johnson 1981). Under normal conditions, a site with an 80- to 90-ft. site index should produce 15- to 20-ft. tall trees in 10 to 15 years. At that time, if necessary, individual oaks can be released by deadening or by cutting competing trees.

PLANTING OAK SEEDLINGS

Planting bottomland oak seedlings is a reliable method of reforestation. When done correctly, the chances for successful establishment of a forest plantation are high (Allen and Kennedy 1989, Kennedy and others 1987, Kennedy 1984). If the planting is done incorrectly or carelessly, however, the project could be an expensive failure. Keys to successful initial establishment of seedlings, in addition to selecting the appropriate species for the site, are obtaining good-quality seedlings, ensuring good preplanting care of seedlings, and using proper planting procedures.

The primary sources of tree seedlings are State forestry organizations and private nurseries. The seedlings available from most nurseries are bare-rooted—separated from the soil they were grown in at the nursery. Bare-rooted seedlings are less expensive than container-grown seedlings, lighter, easier to transport, and easier to plant.

In contrast to pine seedlings, which are usually planted while still quite small, oak seedlings should have a top length of at least 18 in. and a root-collar diameter of at least $\frac{3}{8}$ in. Roots should be well developed and can be pruned to a length of about 8 in. to make planting easier.

Bare-rooted seedlings require careful handling; the roots are very tender and vulnerable. Seedlings generally come from the nursery wrapped in bundles of 50 to 200. If the seedlings are not to be planted immediately, they should be stored (still bundled) in a cool, dark place—ideally in a cold-storage unit. A barn, shed, or dense shade will do for a few days, as long as the roots do not freeze or dry out.

Only as many seedlings as can be planted in 1 day should be taken to the field. They should either be taken out of the nursery-supplied bundles and planted immediately or transferred in small groups to a bucket or planting bag containing moist sphagnum or peat moss. They should never be carried in the hand while planting; doing so will expose roots to the drying effects of the air and sun, and roots will dry very quickly.

The best time to plant bare-rooted oak seedlings is while they are dormant and when the soil is moist—generally, from January through March in the South. Planting can be extended into May if the seedlings are kept in cold storage until planting.

Spacings of 10 by 10 ft. or 12 by 12 ft. are recommended for timber production. However, if the goal is to reforest primarily for wildlife, spacings of 12 by 12, 15 by 15, or even 20 by 20 ft. may meet the objective.

Seedlings can be hand planted using a dibble bar, tile spade, or sharpshooter shovel. It is important that the roots be placed in the hole so they can spread out somewhat naturally—they should not be twisted, balled up, or bent. Moist soil should be packed firmly around the roots.

Perhaps the most frequent planting mistake is planting the seedling either too deep or, more commonly, not deep enough. Seedlings should be planted with the root collar just below the soil surface. Making holes too shallow for proper placement of roots causes "J-rooting," which can result in malformed root systems. Another mistake is leaving an air pocket around the roots after closing the hole, which may allow the roots to dry out.

One experienced person can plant 600 to 800 seedlings per day if planting conditions are relatively good. This rate can vary substantially, however, for a number of reasons, including degree of site preparation, temperature, and the size of the seedlings being planted.

Machine planting is usually much faster than hand planting. An experienced crew of two or three can plant 4,000 to 10,000 seedlings per day with a planting machine. Often survival will be better than that achieved by hand planting.

Early Plantation Development

The landowner should closely monitor development of the new plantation. Problems are likely to show up in the first 2 years after planting. Outright failures and partially successful oak plantations occur occasionally. Seedling mortality and poor growth result from extended post-planting dry periods, flooding coupled with high temperatures, poor planting or seeding practices, residual herbicides or herbicide drift from nearby aerial applications, poor-quality seed or seedlings, or animal depredation.

Early weed control (by disking, mowing, or use of herbicides) will speed growth of seedlings during the first few years and perhaps slightly increase survival, but the benefits may not justify the costs. Too much weed control might actually reduce the short-term value of the site for some types of wildlife that use the weeds for food or cover.

There is no cost-effective method to protect newly established seeds or seedlings from animal predation. Domestic animals, birds, deer, rabbits, squirrels, raccoons, beavers, nutria, and mice may all destroy seeds or seedlings. Fencing to control domestic animals and some wildlife, and good site preparation to clear ground cover, can reduce the number of rodents. Protection of individual seedlings is justified only where there is a high population of nutria. In such a case, chicken-wire predator guards are essential. Some animal damage should be expected and tolerated.

As long as the survival rate is satisfactory, landowners should not worry if trees grow slowly at first (Allen and Kennedy 1989). Most species of oak grow only 1 to 2 ft. per year the first several years. After this stage, growth can increase to 3 to 4 ft. per year if seedlings are dominant and not overtopped. By the end of 10 years, trees should be from 15 to 25 ft. tall or more and constitute a valuable, productive forest.

A number of successful oak plantations established by direct-seeding and planting seedlings have been reported. Johnson and Krinard (1987) reported results of an oak plantation established by direct-seeding: after 10 to 15 years, oaks were 15 to 20 ft. tall with about 250 trees per acre in the dominant/codominant position and a free-to-grow condition. After 10 growing seasons, four oak species established with 1-0 bareroot seedlings in a minor stream bottom in Arkansas ranged from 1.7 in. d.b.h. and 12.9 ft. high for swamp chestnut oak to 3.1 in. d.b.h. and 23.9 ft. high for water oak (Kennedy and others 1987). After 27 years, water oak plantings on an old-field loessial soil in Louisiana had per-acre stand values as follows: number of trees, 356; average d.b.h., 6.6 in.; basal area, 86 ft^2; total volume of trees $\geq$5.0 in. d.b.h., 2,017 ft^2; average height of 50 tallest trees, 61 ft. (Krinard and Johnson 1988). Planting cherrybark oak on abandoned fields in the loess hills appears to be a reliable method for establishing a valuable oak component (Krinard and Francis 1983). At age 20, cherrybark averaged 346 trees per acre. Diameters of the dominant and codominant trees ranged from 6.2 to 9.5 in. d.b.h. and heights from 55 to 65 ft.

OUTLOOK

The oak component in certain bottomland areas can be increased by direct-seeding or planting. Oaks likely to be seeded or planted successfully include Nuttall, water, cherrybark, Shumard, willow (*Q. phellos* L.), white (*Q. alba* L.), and swamp chestnut (*Q. michauxii* Nutt.). Successful regeneration can be enhanced by careful matching of species and site and rigorous attention to meeting site preparation needs. If the procedures and techniques recommended in this paper are not followed, costly failures are likely. The long-term outlook is for an increasing acreage of bottomland to be successfully regenerated to oak.

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Artificial Regeneration of Oaks in the Uplands

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ABSTRACT

Opportunities for planting and seeding oaks in upland sites have never been greater. Land managers are making strong commitments to regenerating oaks, and artificial regeneration can be an important contribution to a successful operation. Direct seeding and planting of oaks can be used to regenerate upland mixed oak stands that have had high mortality from gypsy moth and/or to augment natural regeneration in harvested stands. Results from northern red oak direct seeding and planting studies at upland sites in Pennsylvania are summarized. Direct seeding is recommended only if your are certain that there will be no predation by small mammals. My current recommendation for planting seedlings on upland forested sites is to require appropriate planting procedures, acceptable seedling quality, and freedom from overstory and understory competition.

INTRODUCTION

Development of effective methods for establishing oak seedlings from artificial regeneration on upland forested sites has been hindered by many factors affecting seed germination and seedling growth. The main factors are: (1) overstory tree competition or interference; (2) understory vegetation interference; (3) predation by large and small omnivores; (4) physical environment; and (5) insects and diseases. Each factor has an impact on the successful establishment of a seedling. However, many of these are interrelated, and when working in concert create conditions that are unfavorable to establishing oak seedlings in acceptable time frames.

The literature on seed storage, seed germination, and seedling growth of oaks on upland sites is abundant. A variety of regeneration methods or guidelines have been developed for regenerating oak stands. Some of these include planting of acorns (Johnson and Krinard 1985) or seedlings (Johnson and others 1986), but most assume natural regeneration (Gottschalk 1983, Hannah 1987, Roach and Gingrich 1968, Sander 1988, Watt 1979). To optimize these methods, we need to understand acorn storage and germination requirements. Burns and Honkala (1990) summarized the flowering, fruiting, seed production, dissemination, and seedling development knowledge for the oaks. Cecich (1991) has summarized his understanding of seed production in oaks. Schopmeyer (1974) provided abundant general and oak-specific seed biology and development information.

McQuilkin (1983) concluded that the principal requirements for obtaining successful oak regeneration are moist, friable soils and acorns protected from desiccation and freezing. For acorns not buried in the soil, a cover of leaf litter is essential. Johnson (1970) and Shipman (1962) reported that depth of sowing influenced germination rate and success. Johnson (1967) also found lower germination success for Nuttall oak acorns planted in bare soil than those planted in litter covered soil. These investigators cited soil temperature and moisture as factors controlling germination rate and germination success. Swank and Vose (1988) reported on changes that cutting practices have on the micro-environment of the forest floor and soil. They concluded that the temporal changes in the physical, chemical, and biological properties of the forest floor and soil were important in controlling the success of hardwood regeneration. Little is known about how changes in the forest floor properties may affect the establishment and initial growth of artificially regenerated oaks.

Interference from competing vegetation is probably the most consistent factor contributing to oak regeneration failures in old fields (Bey and others 1975, Hilt 1977, von Althen 1977). In recent years, chemical weed control programs have been developed for establishing several valuable hardwood species on old field sites (Holt and others 1981). These control programs employ a variety of pre- and post-emergence herbicides to gain effective weed control. Typically these programs involve the elimination of existing annual and perennial vegetation before planting using broad-spectrum, foliar applied herbicides, such as glyphosate. Soil active pre-emergence herbicides may also be applied either before or after seedling planting to provide continued weed control throughout the growing season. Effective herbicides include simazine, oryzalin, diphenamid, napropamide, oxadiazon, oxyfluorfen, and metolachlor (Sam and others 1985) and sulfometuron methyl (McCormick and others 1991, Groninger and McCormick 1991, Horsley and others 1992). The specific herbicide or herbicide combinations used in a weed control program depends upon the sensitivity of the planted species to the herbicide, nature of the vegetation to be controlled, and soil-site conditions.

Stress of herbaceous vegetation on hardwood regeneration in forested areas is being recognized (Bowersox and McCormick 1987, Horsley 1982, Horsley 1988, Kolb and others 1989, Kolb and others 1990, McCormick and Bowersox 1989). Regenerating harvested forest lands with desirable timber species is frequently hindered by the presence of competing herbaceous vegetation. These competitors can assume a dominant role in areas where they were either absent or sparse before overstory removal. Some ferns and grasses can rapidly capitalize on changes in site conditions created by overstory removal. Unfortunately the actual factor(s) (i.e., increased light, nutrients, or moisture) responsible for establishing herbaceous species are not well understood. Equally uncertain is the degree that herbaceous vegetation will contribute to the survival and growth of oak seedlings.

There has been no great enthusiasm for artificially regenerating oak in Pennsylvania. Oak stands that have been the product of direct-seeding or planting are rare in Pennsylvania. Successful practices to direct-seed or plant oak seedlings developed for other locations (Johnson and Krinard 1985, Johnson and others 1986) could be used to revegetate or avoid natural regeneration failures. In mixed oak stands impacted by gypsy moth, oak seedlings accounted for 4 to 18 percent of the natural regeneration (Allen and Bowersox 1989). The Allegheny National Forest has a northern red oak planting program to restore oaks to about 2,000 acres that have suffered high overstory mortality following gypsy moth defoliations (Crothers 1992).

In 1984, Penn State started a research program to examine some of the factors controlling the establishment and growth of northern red oak (*Quercus rubra* L.). We restricted our studies to mixed oak stands growing on better-than-average site quality (oak site indices >70) which have little or no natural oak regeneration. Our goal has been to determine the steps necessary to achieve seedlings that are 1.5 m tall in 4 years or less.

This paper summarizes the results of our direct seeding and planting on upland sites in Pennsylvania. Recent information on germination and seedling growth from direct seeding, and tree improvement programs, nursery practices, planting procedures, seedling cultural practices, and methods will be summarized.

DIRECT-SEEDING

Seeding acorns has been widely recommended as a way to regenerate oaks. Graves (1910) recommended planting acorns "in their permanent place" because of the difficulty in transplanting oaks.

Direct-seeding of oaks has the attraction of requiring less time, effort, and expense than the production and planting of seedlings. Acorn storage, seed quality, timing of the seeding, and placement of the acorns are well known elements that influence establishing seedlings. Davidson (1988), Johnson and Krinard (1985) and Teclaw and Isebrands (1991) have provided recent summaries of artificially regenerating oaks. Our studies with seeded northern red oak acorns resulted in seedlings that averaged 15 to 20 cm high after one growing season, and 20 to 50 cm after two growing seasons (Kolb and others 1989, Kolb and others 1990). Preliminary results at the Harry's Valley and Sand Knob 1 locations (figure 1) have shown that shade and competition from fern and grass communities can have a major affect on seedling growth. We direct-seeded northern red oak to evaluate the effect of different nursery and planting practices on seedling survival and growth (Zaczek and others 1991). The study was conducted in clearcut mixed oak stands at three locations: Michaux 1, Harry's Valley 2, and Potter (figure 1). Over all locations, the first-year average height of the standard 1-0 bareroot seedlings was about 30 cm compared to about 20 cm for the direct-seeded seedlings. The bareroot seedlings averaged about 20 cm when planted. At the end of three growing seasons, there was no difference in the average height of seedlings from the direct-seeding (65 cm) and those from the bareroot planting (70 cm).

Anyone who has tried to grow oaks from seed has experienced acorn losses to small mammals. Small mammals can impact a seeding program by destroying or removing the acorns or by clipping the developing seedlings. Table 1 is a list of the small mammals that have major impacts in Pennsylvania. Impact of small mammals is difficult to predict and control. In regard to natural regeneration, Healy (1988) discussed seed predation by birds and mammals and concluded that losses are not sufficient to cause natural regeneration failures. He suggested that, over a long period of time, there should be sufficient supplies of acorns to meet the needs of wildlife and to accumulate adequate numbers of advanced oak seedlings to regenerate a stand. However, I believe that predation pressure on direct seeded acorns will be more intense than on natural supplies because of fewer acorns sown and availability of alternate acorns is low.

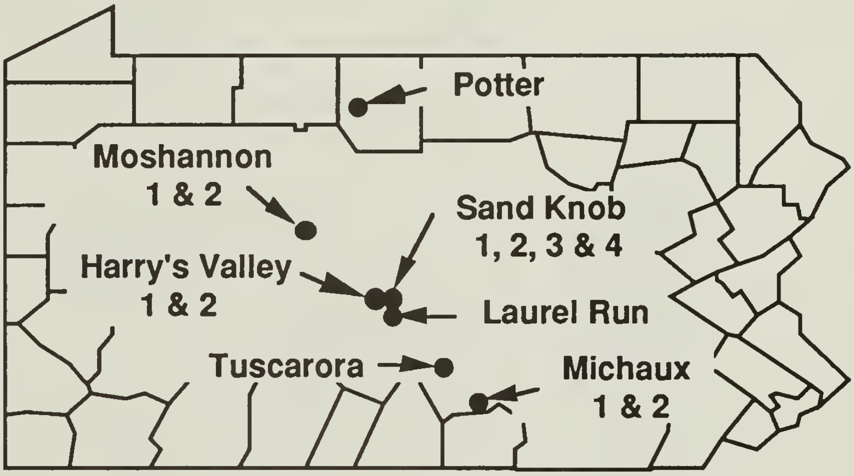

Figure 1—Locations of oak seeding and planting studies in Pennsylvania.

Table 1—Small mammals that can have major impacts on oak regeneration in upland sites of Pennsylvania

Common name	Scientific name	Type
Mice		
White-footed mouse	(*Peromyscus leucopus*)	Omnivore
Voles		
Meadow vole	(*Microtus pennsylvanicus*)	Herbivore
Southern red-backed vole	(*Clethrionomys gapperi*)	Omnivore
Chipmunks		
Eastern chipmunk	(*Tamias striatus*)	Omnivore
Squirrels		
Fox squirrel	(*Sciurus niger*)	Omnivore
Gray squirrel	(*Sciurus carolinensis*)	Omnivore
Southern flying squirrel	(*Glaucomys volans*)	Omnivore

We experienced losses to small mammals that varied from none to complete disappearance of nearly all acorns planted. In one seeding attempt, we repeatedly experienced total losses overnight. In another study, we had greater variability in germination success among three locations than with whether or not the acorns were protected from small mammals (Zaczek and others 1991). Over all three locations, 59 percent of the unprotected acorns germinated, compared to 70 percent of the protected acorns. Only 29 percent of all acorns planted at a southern location (Michaux 1) germinated, whereas 75 and 91 percent of the acorns germinated at the central (Harry's Valley 2) and northern (Potter) locations, respectively.

DeLong (1992) recently studied the predation on direct-seeded acorns. She has observed the losses of direct-seeded acorns in relation to time of placement, depth of placement, and overstory stand condition. This study with unprotected northern red oak acorns in mixed oak stands (Sand Knob 2, 3, and 4) has found that nearly all acorns seeded never develop into seedlings. Eight hundred seed spots were located in uncut (100 percent stocked), improvement (70 percent stocked) and shelterwood (20 percent stocked) treatment areas. Each of the 2,400 seed spots were seeded in October and examined seven times between the seeding and June of the following year. Acorns removed or destroyed were immediately replaced with another sound acorn. In a year following low acorn production (1990), the direct-seeding produced four seedlings by the end of one growing season. In a year following average acorn production (1991), the direct-seeding resulted in 193 seedlings at the end of one growing season. The losses were similar for acorns placed on the surface and those planted 2 cm into the soil. The highest losses were in the shelterwood treatment, with lower losses in the improvement treatment and uncut stand. Based on the evidence at the seed spot, most of the acorns were lost to white-footed mice (*Peromyscus leucopus*).

Not willing to risk the success of our research efforts to the chance of predation by small mammals, we developed two methods for protecting acorns: A small protector was designed for establishing a single seedling from spring seedings (figure 2); a larger protector was developed for studies requiring minimal disturbance to the litter and soil and for use with fall seedings (figure 3).

The single seedling protector was made from 2.5-cm diameter, schedule 40 PVC pipe that is cut lengthwise. The bisected pipe was cut into 12-15 cm sections, with a cross-cut at the top and a 45° angle cut at the bottom. Angle cuts made it easier to insert the protector into the soil. The two halves have been secured at one or two points with one and one-half wraps of masking tape. The protector was inserted at least 10 cm into an augured hole. An acorn was added, covered by a suitable material to conserve acorn moisture and a 4-cm nail was place across the top to prevent extraction of the acorn. This type of protector has been used successfully with northern red oak, white ash, and white pine (Kolb and others 1990). Small mammals occasionally excavated a properly installed protector (< 1 percent). Small mammals will excavate protectors that are placed < 10 cm into the ground or protectors that are loosely inserted into the soil. This protector has been susceptible to over-winter frost heaving in waterlogged soils.

The larger protector was made from 160 cm diameter ASTM 2729 PVC pipe cut in to 12 to 15-cm lengths. The pipe was inserted at least 5 cm into the soil. Insertion into rocky, root-laden soil has been accomplished by 160-cm ring bore to the desired depth, and then the pipe was pushed into the slit. After the pipe was

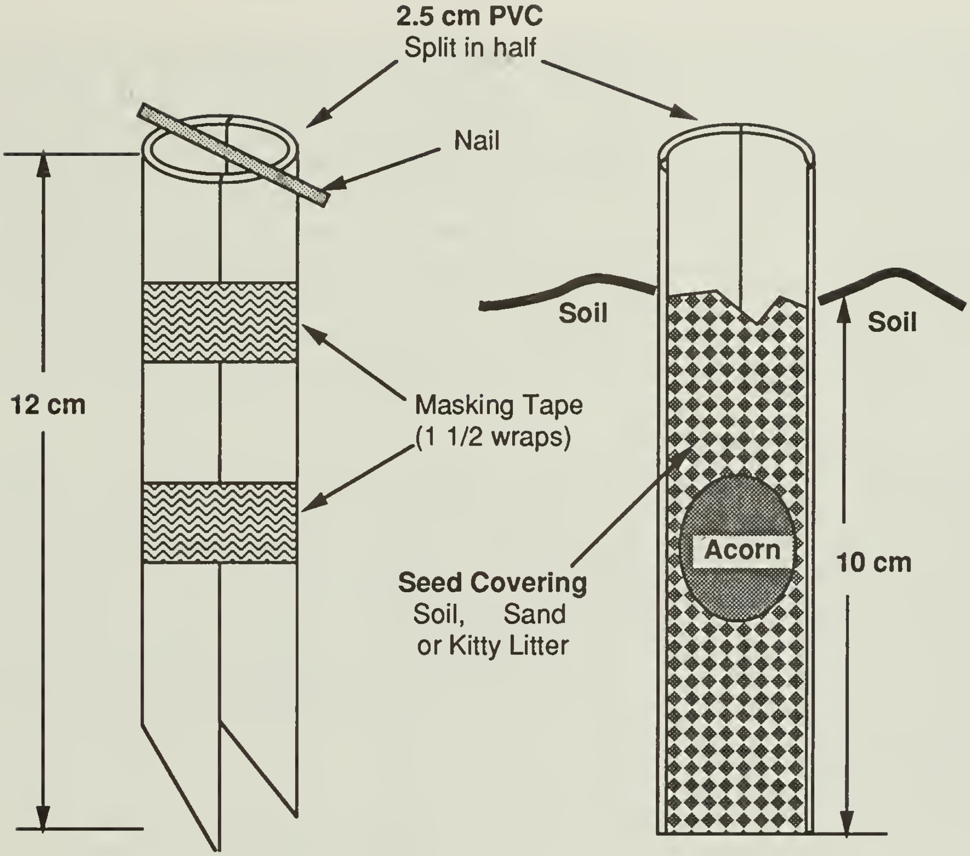

Figure 2—Individual acorn protector used at the Pennsylvania State University.

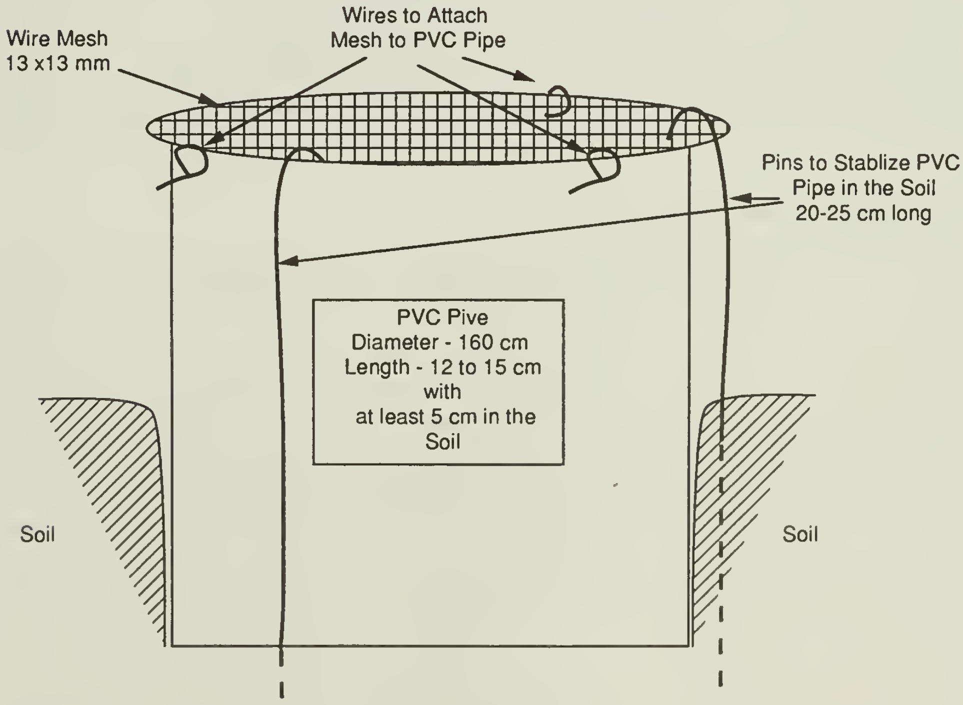

Figure 3—Large acorn protector used at the Pennsylvania State University.

in place, the acorns were planted and the top was covered by 1.3-cm mesh wire that was attached to the top of the pipe at three or four points. Gaps between the pipe lip and the mesh had to be <1.5 cm to exclude the mice-sized animals. Finally, the protector was pinned to the soil by three to four wires, 20-25 cm long. This protector has permitted us to conduct phytotoxicity tests on seeds and germinating seedlings with soil-applied herbicides (McCormick and others 1990). We are using this protector to evaluate the effects of varying amounts of litter, acorn placement, and overstory conditions on the storage, germination, and growth of northern red oak from fall plantings. This protector has been susceptible to winter frost heaving in waterlogged soils and has not protected the acorns from losses to raccoons, black bears, or humans.

We are trying to develop a degradable acorn protector. One device has worked well in a trial. The trial was conducted in the same stands as the acorn predation study (Sand Knob 2, 3, and 4) in the year with an average acorn crop. Degradable protectors containing northern red oak acorns were planted 5 cm deep in October 1990. In August 1991, each protector was evaluated. About 44 percent of the protectors produced a seedling (table 2). This was lower than the >70 percent germination success expected from the PVC protectors but greater than the <10 percent success from the unprotected acorns in the predation study.

Table 2—Fate of northern red oak acorns planted in a prototype degradable seed protector[1]

Fate	Number	Percent
Successful seedling	66	44
Protector removed	13	9
Germinated but no seedling	39	26
No apparent germination	32	21

[1] Seeding was done in October and placed 2-3 cm below soil surface.

All small mammals listed in table 1 have the potential to feed on newly germinated shoots. Meadow voles, southern red-backed voles, and white-footed mice are more likely to clip off new shoots than the other species. In some cases the shoots are consumed, in other cases the shoots are simply clipped off and not eaten. It is likely that much of the small mammal clipping of newly emerged oak shoots has been blamed on deer, insects, or disease. A careful examination shortly after the clipping is necessary to determine the precise cause of a decapitation to a newly emerged oak shoot. Stormer (1968) studied the shoot clipping habits of white-footed mice. He concluded that the clipping activity was more related to their propensity to gnaw and not related to their needs for food or water.

In November 1989, we direct-seeded northern red oak into shelterwood (20 percent stocking) and improvement (70 percent stocking) treatments made in a mixed oak stand (Sand Knob 2 and 3). Most of the acorn protectors were disturbed by humans and then pilfered by small mammals. From a limited database following a year of low acorn production, we observed frequent clipping of the emerging shoots by small mammals. In the 1990 growing season, 46 percent of the acorns that were going to germinate had germinated by June 1. Small mammals clipped off one-half of these seedlings. By June 21, 73 percent of the potential germinants had shoots and still about one-half of these were clipped off by small mammals. Clipping activity dropped sharply after July 1. The study was duplicated with November seedings in 1990. Small mammals clipped about 1 percent of the potential germinants in the improvement area and about 5 percent of the potential germinants in the shelterwood area. Most of the clipping activity was before July 1. All clipping action was a single event; we recorded no multiple clippings.

Studies examining the germination and growth of direct-seeded northern red oak at the Moshannon location were also conducted in the 1990 and 1991 growing seasons. These studies were in a mixed oak stand that had clearcut and uncut treatments. Germination success in 1990 averaged about 60 and 70 percent for the clearcut and uncut areas, respectively. Clipping by small mammals was < 1 percent in the clearcut area. In the uncut area, the June 25 inventories recorded about 25 percent of the emerged shoots were clipped by small mammals. Replicated direct-seedings into new treatment areas in 1991 had germination success of about 75 and 85 percent in the clearcut and uncut areas, respectively. Again there were < 1 percent of the seedlings clipped off by small mammals in the clearcut areas. Clipping by small mammals dropped to < 10 percent in the uncut area. Preliminary data for 2 years after seeding indicated there was no difference in survival or average height of the clipped and unclipped seedlings.

Small mammals can be a major factor in determining the success of oak direct-seeding on upland sites. From our experiences, small mammals will either consume or move most unprotected direct-seeded acorns. I am convinced that most direct-seeding of acorns in upland sites will fail to produce seedlings unless the acorns are protected from small mammals. In addition, preliminary information from our studies indicate that of those acorns that germinate some will be clipped off by small mammals.

The clipping has been limited to a one-time decapitation, usually early in the growing season. I do not believe this clipping activity will be a major problem unless there would be multiple clippings in the growing season.

PLANTING

In 1984 we planted 1-0 bareroot northern red oak seedlings at three locations (Harry's Valley 1, Laurel Run, and Sand Knob 1). This project was designed to evaluate the effect of established ferns and grass communities on the survival and growth of oak seedlings. Overall survival and growth rates were encouraging (George and others 1991). Four-year survival was 58 percent for seedlings growing in the presence of ferns and grasses and 81 percent for those growing free from fern and grass interference. Average 4-year height was 1.1 and 1.3 m for the weedy and weed-free conditions.

Root system morphology and structure make it difficult to produce easily transplantable oak seedlings. Nursery practices of varying plant densities, undercutting the root, and lateral root pruning have been used to reorganize the root systems to increase survival and growth rates. It is generally agreed that post-planting growth rates are dependent on the ability of the seedling to develop a root system that has established good contact with the soil water and nutrient resources. Ruehle and Kormanik (1986) have found that lateral root systems varied among families, and the number of large first-order lateral roots were correlated with after-planting growth potential. Schultz and Thompson (1991) suggest that at least six first-order lateral roots are needed for acceptable survival and growth of oak seedlings planted in the prairie region of the Central States. Barden and Bowersox (1989, 1990) reported that clipping the newly emerged radical will create a fourfold increase in the number of "taproots." We also found that new root development was mainly from the cut ends of any of the larger root tissues. Furthermore, Barden and Bowersox (1991) found that 1-0 seedlings that were established in the nursery with the radical clipped also performed better when out-planted than seedlings with unclipped radicals.

We are concluding a study that evaluated a variety of nursery stock types at three locations (Michaux, Harry's Valley 2, and Potter). Location had a strong effect on the 3-year-old height. Over all treatments, average height at the Harry's valley location of 1.3 m was greater than the average height at Michaux (0.6 m) and Potter (0.9 m). One half of the seedlings for all treatments were top-clipped to a 10 cm height at planting. Clipping resulted in greater 3-year height growth than the unclipped seedlings, but there was essentially no difference in the total height at the end of three growing seasons. Over all treatments, 2-year-old stock had an average height of 1.2 m. This was 62 percent greater than the average 3-year-old height of the 1-year-old stock. Undercutting in the nursery bed produced variable results but was most beneficial for the 2-year-old stock. Greatest 3-year heights occurred in 2-0 container stock, which averaged 1.5 m tall. We concluded that the 2-0 bareroot seedlings would be an acceptable balance between seedling production, planting limitations, and out-planting performance variables for planting northern red oak seedlings in the upland conditions of Pennsylvania. Annual undercutting the seedlings will produce a more plantable root system and should improve the out-planted height growth.

Planting oak seedlings in upland sites in Pennsylvania has been an endurance test for planting crews. Most of the stands have between 10 and 90 percent of the surface covered by rocks. The KBC bar has been the best choice for hand planting and will create and close a 16-cm deep hole on most sites. However, this planting method restricts the size and arrangement of the root systems that can be planted. Roots longer than 16 cm and wider than 10 cm needed to be removed before planting. Tree planters would discard seedlings with the larger, more developed root systems because they could not make a hole big enough to accommodate the root systems.

These soil conditions and the resulting planting procedures were seriously limiting seedling characteristics. One-person augers have been used successfully for planting trees in the hard, rocky soils in the inter-mountain region of the Rocky Mountains. We also found these augers worked for planting oak in the Pennsylvania uplands. We use a 10-cm, carbide-tipped auger powered by a chainsaw engine with a slow speed gearhead. We auger a 30-cm deep planting hole. Loose soil that falls back into a 30-cm hole is easily removed by hand before inserting the roots. One or two additional holes are needed to accumulate sufficient soil to plant the seedling. This method of planting is being used to plant northern red oak seedlings on about 2,000 acres in the Allegheny National Forest (Crothers 1991).

Pennsylvania's Bureau of Forestry and Pennsylvania State University have started a cooperative genetic improvement program for northern red oak (Bailey and others 1992). The objective of the program is to identify families that can achieve a 1.4-m height in 3 years after out-planting. The study is being conducted at three locations (Michaux 2, Tuscarora, and Moshannon 2). All seedlings are plantings in recently clearcut mixed oak stands, maintained weed free, and fenced to exclude deer. The 2-year-old survival values for all families planted in 1990 were >96 percent at all locations. Over all families, average height was greatest at Tuscarora (0.8 cm), moderate at Michaux 2 (0.5 cm), and lowest at Moshannon 2 (0.4 cm). Family means ranged from 0.37 to 0.5 cm at Moshannon 2 to 0.6 to 1.0 cm at Tuscarora. These results were for seedlings planted as 1-0 bareroot stock, and 1991 was a very dry year in Pennsylvania. Progeny from about 40 parent trees have been planted as 2-0 stock in 1991 and 1992 and will be planted in 1993 and 1994. In total, we plant to screen about 180 parent trees.

SUMMARY AND CONCLUSIONS

Research programs have been aggressively studying direct seeding and planting of oak throughout the eastern hardwood region. This is particularly true for northern red oak. We have gained valuable foundational information on the elements affecting germination and seedling growth from direct seeding. To establish one oak seedling from direct-seeding, I recommend planting two to three viable acorns per spot—two acorns for spring seedings, three for fall seedings. Each acorn should be planted 25-50 cm deep in the soil. Overstory and understory competition needs to be reduced to a level that will permit the seedling to compete with the other ground-level vegetation. I do not recommend direct-seeding acorns in upland forest sites unless you are certain that there will be no small mammal predation or the acorns will be protected from predation.

Successful establishment and growth of oak seedlings from planting require appropriate planting procedures, acceptable seedling quality, and freedom from overstory and understory competition. There is considerable variability in size and root characteristics of oak seedlings that are available at any one time. Smaller seedlings being planted in unrestricted soils can effectively be planted with bars, whereas larger seedlings being planted in rocky soils are best planted with an auger. With all things being equal, I recommend planting seedlings that are at least 30 cm tall, have a root collar of 6 mm, and have a multiple-branched, 25-cm-long root system. Seedlings with these minimum characteristics are best planted with an auger, especially in rocky upland forest soils. Overstory and understory competition should be reduced to a level that the seedlings are capable of successfully competing with the understory vegetation. In most cases, this would be to reduce the overstory to <50 percent of crown cover and remove all over-topping understory vegetation.

Tree improvement programs, nursery practices, and planting procedures will provide additional information to have more successful planting programs. Our knowledge of the cultural requirements to gain acceptable post-planting seedling height growth rates is developing to the point were prescriptions will soon be formulated. Refinements and adjustments will be needed for specialized situations and for individual species. We are ready to move to a higher level of understanding of the factors controlling successful artificial regenerating oaks in upland conditions. However, production-scale artificial regeneration trials are needed to test the practical application of our current knowledge. Implemention of the current technology is key to the future of developing practical artificial regeneration programs for oaks in the uplands of eastern North America.

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Oak Plantation Establishment Using Mechanical, Burning, and Herbicide Treatments

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ABSTRACT

Mechanical methods, prescribed burning, and herbicide treatments for establishing oak plantations are reviewed, with emphasis on herbicides. Integrated prescriptions for site preparation using these silvicultural tools are outlined for both clearcut forests and old field sites. The basic premise is that intensive cultural treatments will be required for repeated success in establishing oak plantations using either seeding or planting, when advanced natural regeneration or adequate seed trees are not present. Intensive treatments to promote rapid seedling growth appear critical to minimize the intensity and duration of animal predation on oak regeneration. Labeled herbicides and appropriate application techniques for both woody and herbaceous control are reviewed along with approaches for expanding existing labels and registering new herbicides for oak culture.

INTRODUCTION

Much research attests to the fact that oak plantations probably cannot be established consistently without intensive site preparation, herbaceous weed control, and continued release from invading competitors (Malac and Heeren 1979, Kennedy 1981, Woodrum 1982, Nix 1989). Oak seedlings, like most plants, generally grow better in a competitor-free space, although not always as rapidly as other tree species (Sam and others 1986, Bowersox and McCormick 1987, George and others 1991). Why this is so is not completely clear, but it appears partly due to the slower early growth habit of many oak species, and their propensity to allocate photosynthates into root storage and root growth instead of top growth. There has been ample research demonstrating accelerated early growth of oaks after vegetation control to warrant its use (Aust and others 1985, Krinard and Kennedy 1987, Wendel and Lamson 1987, Miller and Burkhardt 1987, Johnson and others 1989). However, the investment-return outcome for such intensive culture is yet unknown and will remain unknown for some time.

PRINCIPLES OF COMPETITION CONTROL

Over the past decade several principles of vegetation management for plantation establishment have been discovered through extensive research, mainly on conifer species. A summary of these principles that should apply to oak culture includes:

1. Vegetation control can increase tree growth by the greatest proportion in years 1-3, especially when near complete control is achieved around large, healthy

seedlings that have been properly planted, and are not injured by the vegetation control treatments.

2. Early growth gains from years 1-3 are maintained and amplified well into the rotation.
3. Threshold levels of competition reduction must be achieved before a positive growth response occurs, and a point of diminishing returns also exists where additional control gains no further growth response.
4. Plants immediately surrounding crop-tree seedlings are the strongest competitors and should be the main target for control.
5. A mixture of grasses, ferns, forbs, vines, and woody resprouts present severe competition to tree seedlings, but grasses and ferns are the most competitive in the early stages from years 1-5.
6. Woody plants become established in greatest numbers during the first year after clearcut harvesting, while some immigration is continuous.
7. The most severe woody competitors are tree species, not shrubs, that can grow equally with crop trees and maintain a position in the main canopy. Resprouting hardwoods are the most severe woody competitors to planted seedlings.
8. Following mechanical site preparation, woody competition starts exerting its influence in years 5-8, but woody control is most cost-effective prior to planting or in years 1-2.
9. Tree diameters respond proportionally more than heights to competition control.
10. Projected returns on investments in intensive site preparation treatments are usually justified only on sites of medium to high quality unless treatments are necessary to guarantee survival because of management objectives.

Besides competition control, it is known that oak seedlings benefit from soil tillage (both surface and subsoil) with assumed benefits in aiding rapid root development (Plass and Green 1963, Woodrum 1982, Seifert and others 1985, Nix 1989). It is also assumed that site preparation requirements will probably be more stringent for oak seeding than for seedling planting (Bullard and others 1992). It is recognized that these principles and concepts will require further verification for specific oak species as they interact with the multitude of sites and plant community situations.

GENERAL PLANTATION ESTABLISHMENT PRESCRIPTION

A proposed general prescription for oak plantation establishment is that large, healthy seedlings should be properly planted on tilled and appropriately subsoiled sites having minimum hardwood competition, with herbaceous vegetation control treatments applied annually for 2 to 3 years (Malac and Heeren 1979, von Althen 1987). Both woody and herbaceous control treatments must be very effective to realize a return on their investment. Because of the constant immigration of hardwoods into young stands (Cain and Yaussy 1984), woody control treatments should be performed at regular intervals as needed. Hannah (1987) summarized: "The key . . . is to control competing vegetation, keeping the oaks dominant and free to grow." Johnson and others (1989) summarized their understanding: "The abundance of red oak in the herbicide-treated clearcut suggests that the key to regenerating red oak may be competition control and not necessarily a long regeneration period."

Rapid early seedling growth is critical to oak establishment to minimize predation from deer, rabbits, and rodents. Only through enhanced early growth can the time spent in vulnerable stages be shortened. (However, rapid early growth begs the issue of eventual log quality as it is affected by a large juvenile wood core (Maeglin 1987).) At the same time, site preparation treatments must work in concert with the overall management plan and safeguard the multi-resource values of the forest, maintain or improve long-term soil productivity, and protect intrinsic site values.

SITE PREPARATION FOR CLEARCUT SITES

Intensive site preparation treatments on cutover forest sites often require the integrated use of mechanical, burning, and herbicide treatments.

Mechanical Treatments

The advantages of using mechanical site preparation treatments before planting or seeding are numerous. Logging slash can be pushed into piles or windrows using rootraking or processed with choppers or flailers. Rootraking is also used to dislodge woody plant roots, minimizing woody competition and increasing available nutrients and water for crop tree growth (Burger and Pritchett 1988). The clearing of slash then permits other soil amelioration treatments—disking, bedding, and subsoiling.

Morris and Lowery (1988) reviewed site preparation research in the South and concluded that only disking, bedding, and subsoiling are likely to have large positive effects on tree growth. On upland and poorly drained sites, disking has been shown to benefit oak establishment (Woodrum 1982, Seifert and others 1985, Nix 1989). On poorly drained sites, bedding has yielded short-term growth increases that may be maintained (Seifert and others 1985). Disking increases the rootability of the surface soil across the entire area, while bedding does the same and locally raises the soil above the winter water table (Morris and Lowery 1988). However, the volume of tilled soil is less with bedding compared to disking and root closure between rows may not occur as quickly as on disked sites.

The principal disadvantage of rootraking treatments occurs when valuable site nutrients are displaced into windrows and piles, and away from planting rows and seedling access (Morris and others 1983, Tuttle and others 1985). Further, raked or disked organic matter is made to decompose faster, perhaps before seedling roots can take full advantage of the ensuing nutrient release (Banker and others 1983, Miller and Edwards 1985, Burger and Pritchett 1988). Soil disturbance also clears the organic mulch from the soil surface that aids in preventing evaporative moisture loss. At the same time an abundance of herbaceous plants can become established on the bared soil and represent severe early competition. The herbaceous communities also form excellent rodent habitat that encourages seed and seedling predation. On some sites, revegetation after intensive mechanical scarification is slowed or spotty leading to sheet and rill erosion and nutrient loss (Blackburn and Wood 1990). Only through careful and considerate application of mechanical treatments can these adverse effects be minimized or eliminated.

Subsoiling and ripping are increasingly being used for pine establishment in the South after a history of mixed research results as far as improving both survival and growth (Berry 1979, Lantange and Burger 1983, Wittwer and others 1986). Subsoiling can result in both an increase in the amount of soil exploited by tree roots in the first few years and more uniform depth distribution of roots. Less is known about where and how to apply subsoiling than disking and bedding, but the benefits to deep-rooted species on restrictive soils is obvious. It appears that fracturing of dry pans is preferred to shearing of wet restrictive horizons (Parker and Amos 1982).

There is now a 3-in-1 blade plow manufactured by Symonds, an Australian company, that disks, subsoils (two directions by adding a wing to the ripping blade), and beds in one pass. The 3-in-1 plow has already been used operationally to establish oaks successfully in the South. Another mechanical site preparation tool that could be useful in oak establishment is the Bräcke Scarifer (Alm and others 1988). This scarifier makes discontinuous scarified-mounded planting sites across an area at regularly spaced intervals. About 10 percent of the area is scarified. Oak seeds and seedlings could be planted either in the scarified area or somewhere on the mound—edge to center. Because of the versatility of the hitching arrangement on the scarifier, this implement can be worked in both shelterwood stands and clearcut areas. Seeding and herbicide applications can be simultaneously performed during the operation with added attachments.

Resprouting vigor of hardwoods can be decreased significantly by performing felling or shearing operations after the spring growth flush has depleted root reserves (Zedaker and others 1987, McMinn and Nutter 1988). Performing mechanical treatments during the usually drier summer months should also be more efficient and effective. As the intensity of utilization increases in the future, the need for windrowing or piling treatments will probably decrease, while the need for soil tillage treatments may increase to ameliorate soil compaction caused by intensive harvesting operations.

Prescribed Burning

Prescribed burning is commonly used after mechanical and chemical site preparation to further reduce logging slash and improve planter access. Prescribed fire can, with adequate fuel and proper burning conditions (timing), topkill woody plants that are less than 2-3 in. groundline diameter, but can increase the abundance of annual and biennial herbaceous plants (Langdon 1981, Miller 1982, Danielovich and others 1987, Sanders and others 1987, Yeiser 1992). Perennial grass clumps that are also partially consumed regrow with tender shoots, making them more susceptible to herbicide control. It is also known that repeated burns in a stand prior to harvest, spaced over 5 or more years, can reduce the size of woody plants. Fire can also be used after harvest to accomplish the same effect while reducing logging slash. But after harvest, and more so after methods of scarifying site preparation, fuels are discontinuous and ignition may be difficult and more costly with uneven hardwood control.

Soils are not usually degraded by one or more repeated burns, but developing research would suggest that macropores can be filled and porosity lowered with repeated burning of sandy loam soils, resulting in a depression of soil moisture-holding capacity (Miller and Boyer 1991). Other research has shown that considerable nitrogen, approximately 60 percent of that in the fuel, can be volatilized from the site with a single burn (DeBell and Ralston 1970, Vose and Swank 1992). Long-term inputs of nitrogen from biological fixation and atmospheric inputs may replace the nitrogen lost from fire, but this is not assured (Boring and others 1991).

Herbicide Treatments

Herbicide applications for site preparation before planting oaks can result in the most positive control of woody and herbaceous competition. Modern herbicides are both safe to the applicator and the environment when used according to label instructions (Miller and Mitchell 1988). They can be applied broadcast, to planting rows, or selectively to individual target stems (Newton and Knight 1981, Cantrell 1985, Miller 1987, Miller and Mitchell 1988). It is necessary that the most effective herbicide or tank mix be selected for both the target species on the site and also site constraints. The herbicide(s) should be applied at the most effective time using the correct application procedure.

Soil-active herbicides should be used with a full appreciation of the risk of nontarget plant damage due to residual carryover or application proximity. But it should be recognized that herbicides having both foliar and soil activity are often the most effective. Those herbicides discussed in the following sections are described further in table 1.

Table 1—Herbicides labeled or used for oak culture; manufacturers, active ingredients, and concentrations in formulations

Product	Manufacturer	Active ingredient(s)	Amount of a.i. or a.e. in formulation[1]
AAtrex 4L	Ciba-Geigy	atrazine	4 lb/gal
Access[2]	DowElanco	picloram + triclopyr	1 + 2 lb/gal
Accord and Roundup	Monsanto	glyphosate	4 lb/gal
Arsenal Ac	American Cyanamid	imazapyr	4 lb/gal
Atrazine 4L	Du Pont	atrazine	4 lb/gal
Chopper	American Cyanamid	imazapyr	2 lb/gal
Chopper RTU	American Cyanamid	imazapyr	3.6%
Escort	Du Pont	metsulfuron	60%
Fusilade	ICI	fluazifop	1 lb/gal
Garlon 3A	DowElanco	triclopyr amine	3 lb/gal
Garlon 4	DowElanco	triclopyr ester	4 lb/gal
Oust	Du Pont	sulfometuron	75%
Pathway, Tordon 101R and RTU	DowElanco	2,4-D + picloram	¼ + 1 lb/gal
Princep 4L[3]	Ciba-Geigy	simazine	4 lb/gal
Tordon K[2]	DowElanco	picloram	2 lb/gal
Tordon 101[2]	DowElanco	2,4-D + picloram	½ + 2 lb/gal
Vantage (Poast)	BASF	sethoxydim	1 lb/gal
Weedone 2,4-DP	Union Carbide	2,4-DP amine	4 lb/gal
2,4-D ester	several	2,4-D ester	4 lb/gal

[1] a.i. = active ingredient; a.e. = acid equivalent.

[2] Restricted use herbicides that must be applied by a State certified applicator or permitted private landowner (contact county agent for permit).

[3] Other formulations of simazine are Princep Caliber 90, Princep 4G, and Princep 80W.

Herbicide Labels. The herbicide label is a legal document that specifies on what type of sites and how a herbicide can be applied. Herbicides legally used in forestry must be labeled for "forest sites," or in some instances for "noncrop areas" and "tree farms" when not broadcast for site preparation. In oak establishment, the use of herbicides that do not have one of these site specifications is unlawful and carries a prescribed fine and prison term for violations according to State laws. It is also unlawful to exceed labeled rates and use methods of application not outlined on the label.

Other specifications on a herbicide label, such as crop-tree species and target efficacy, are involved with product performance and manufacturer liability. It may be legal to use a herbicide for oak culture when the label states "for conifer release," but the manufacturer is not liable for poor performance or crop injury. Thus, the discussion of which herbicides are labeled for oak culture is not simple and will have to be qualified in the following discussions. Also, the interpretation of labels may vary by State. The direction and possible avenues of future herbicide development and registration for oak culture will be discussed at the end of this paper.

Timing of Herbicide Applications. Herbicides perform best when applied at times the target plants are most susceptible and/or the crop trees are most resistant to injury (Miller and Bishop 1989). Applying them before or after the correct time reduces or even eliminates their effectiveness and may damage the crop. As far as the most efficient timing of woody control treatments, herbicide applications should only be made after all resprouts have emerged following harvesting, burning, or mechanical disturbance. Woody rootstocks must have sprouts before herbicide activity and control can occur.

Woody Plant Control with Tree Injectors and Backpack Sprayers. The manually applied treatments for woody plant control that should have use for oak establishment are:

- tree injection
- stump sprays
- directed foliar sprays
- basal bark sprays

(Soil spot applications using Velpar L Herbicide by Du Pont appear to have limited use in hardwood culture because of the residual nature of Velpar L.) All sizes of trees and shrubs can be controlled by using the right treatment when the proper herbicide is applied at the correct time. Here are the sizes of woody plants that can be treated most effectively by manual application methods:

Method	Effective size of target stems controlled
Injection	sizes greater than 2 in. d.b.h.
Stump sprays	all sizes
Directed foliar sprays	up to 6 ft. tall
Full basal sprays	up to 6 in. d.b.h.
Streamline basal sprays	up to 2 in. d.b.h.

A combination of methods can be used on the same site when an array of target stem sizes are to be treated. Often, on the same site, tree injection is used for the larger trees, basal or foliar sprays are applied to the smaller woody competitors, and stumps of harvested trees are sprayed.

Tree Injection. Tree injection is the least costly of these herbicide treatments for controlling unwanted trees that are 2 in. in diameter and larger. This method is highly versatile and can be used alone or in combination with other individual stem treatments for site preparation, hardwood release, timber stand improvement, stand conversion, and creating snags for birds and other wildlife. This physically demanding method requires applicators that can repeatedly and precisely chop into tree trunks deep enough to properly deliver herbicide for uptake in the sap flow. Each cut must form a pocket into the sapwood, where the herbicide is placed for uptake. The herbicide should stay in the pocket and not seep out through any split sides, because any herbicide on the bark is wasted. When treating sprouting clumps, each stem must be injected. The variable results that can occur with this method are partially caused by the inability of applicators to penetrate the bark sufficiently or to correctly place the herbicide for uptake.

Common methods of tree injection are:

- tubular tree injectors
- hypo-hatchets
- hack-and-squirt

Tubular tree injectors consist of a long metal tube fitted with a chisel-type blade that is used to cut through the tree bark into the sapwood near the base of the tree. Several models are available. Units are equipped with a lever, handle, or wire that is pulled to deliver the herbicide (usually 1 mL) from the cylinder into the cut. The delivery rate can be adjusted for accurate calibration. To calibrate: fill and prime the injector; pull the handle or wire 10 times while collecting the herbicide in a container graduated in milliliters; if this is not 10 times the desired rate, adjust the lock-nut and repeat the procedure until accurate calibration is achieved. Frequent sharpening and maintenance of injection tools is needed for best results.

The hypo-hatchet consists of a hatchet with an internal herbicide delivery system that is connected by a hose to a herbicide container carried on the back or belt. When the hatchet strikes a tree, the blade must penetrate into the sapwood and the impact drives a piston forward delivering 1 mL of herbicide into the cut. The rate cannot be adjusted. Daily cleaning and lubrication of the impact piston is required maintenance, along with periodic replacement of rubber O-rings and seals. Safety glasses should always be worn when using a hypo-hatchet because of frequent herbicide splashes.

Hack-and-squirt is a method that uses a narrow-bit ax, hatchet, or machete for making the cut, along with a spray or squeeze bottle or oiler to deliver the herbicide. A grinder can be used to narrow the bit of axes and hatchets for easier and better cuts. Most commercial spray bottles are set to deliver 1 mL with each trigger pull, but each must be checked prior to use. Safety glasses also should be worn when using this method. Waist-high injections by the hypo-hatchet and hack-and-squirt methods are just as effective and fast to perform as basal injections.

With larger stems, more herbicide is applied by basal injections because of the larger groundline diameter compared to diameter at breast height.

The amount of herbicide per injection and the edge-to-edge spacing are specified on the herbicide label. Continuous edge-to-edge cuts should be used on hard-to-control species such as dogwood, maple, and hickory. Herbicides labeled for tree injection that have wide control spectrums are:

- Arsenal Ac
- Accord and Roundup
- Chopper
- Garlon 3A
- Pathway, Tordon RTU (Ready To Use), Tordon 101R, and Tordon 101
- 2,4-D

Some of these herbicides have the same active ingredients with new names or a slight difference in formulation (table 1). Accord is the same as Roundup without a surfactant, Chopper is half the concentration of Arsenal Ac, and Pathway is the new name for Tordon RTU and Tordon 101R. Accord will replace Roundup, and Pathway will replace Tordon formulations as the other names are phased out. Efficacy of these herbicides for selected species is presented in table 2.

Table 2—Species susceptibility to injection herbicides under ideal conditions and timing

Herbicide	**Susceptible**		**Moderate**	**Tolerant**
Arsenal Ac/Chopper	Sweetgum Southern red oak Northern red oak White oak Post oak Water oak Chestnut oak Black cherry	Hickory Dogwood Ash Beech Sourwood Blackgum Red maple		Pine Elm
Accord/Roundup	Sweetgum Southern red oak Post oak Blackgum Sourwood		White oak Northern red oak Water oak Red maple Black cherry Dogwood Pine Elm Chestnut oak Beech	Ash Hickory
Garlon 3A	Sweetgum Southern red oak Northern red oak White oak Post oak Hickory	Dogwood Pine Elm Chestnut oak Sourwood	Blackgum Water oak Red maple Black cherry Ash Beech	

Table 2—Species susceptibility to injection herbicides under ideal conditions and timing—(Continued)

Herbicide	Susceptible		Moderate	Tolerant
Pathway/Tordon	Sweetgum	Beech	Red maple	
	Southern red oak	Hickory		
	Northern red oak	Sourwood		
	White oak	Dogwood		
	Post oak	Pine		
	Water oak	Elm		
	Chestnut oak	Ash		
	Black cherry	Blackgum		
2,4-D	Southern red oak		Sweetgum	Water oak
	White oak		Northern red oak	Red maple
	Post oak		Black cherry	Ash
	Blackgum		Hickory	Chestnut oak
	Dogwood		Pine	Beech
	Elm		Sourwood	

Garlon 3A and Accord (Roundup) have the advantage of no soil activity. Of these two, Garlon 3A is preferred because it is effective on more species, especially maple and hickory. Arsenal Ac, although soil active, has the broadest spectrum of control of any of these herbicides and can be used at wider-spaced injection cuts. Garlon 3A and Arsenal Ac are usually applied diluted at 33-50 percent and 5-10 percent, respectively. All products can be applied year-round, except during times of heavy sap flow in the spring. Arsenal and Chopper are most effective when injected from July to October.

Stump Spraying. Stump resprouting of many species can be prevented or decreased by a low-cost herbicide treatment following harvest and after partial cuts for timber stand improvement. Stumps larger than 12 in. diameter do not usually resprout and do not need treating. Of course, other hardwoods may invade an area with time. Hand clearing treatments for release or thinning can be enhanced by treating the stumps with herbicide. Stump spraying after bush-hogging is another treatment alternative. The same herbicides that are used for injection are labeled for stump treatments; also labeled are Chopper and Chopper RTU that have the same active ingredient as Arsenal Ac.

A backpack sprayer can be used that has a wand or spray gun equipped with a straight stream, fan, or hollow-cone nozzle. A sawyer can carry herbicide in a utility spray bottle for treating stumps after cutting. For small-diameter stumps, a wick applicator can be used.

Freshly cut stumps should be treated as soon as possible. Stump treatments within 4 hours of cutting have been most effective—the sooner the better. For stumps over 3 in. in diameter, the outer edge or cambial area must be completely wetted with the herbicide. Smaller stumps are usually completely wetted. To be successful, all small stumps should be treated. Thus it is best that the sawyer or companion applicator treats soon after felling so no stems are skipped. Cutting and herbicide treatments can be performed during late winter and summer. Winter treatments are slightly less effective than growing-season treatments, but only a 60-80 percent control success should ever be expected with stump spraying (Zedaker and others 1987). Older cut stumps can be treated with the streamline basal stem mixture (see that section). The mixture is applied to the outer 1 in. edge of the stump until runoff and to the base of any sprouts.

Directed Foliar Sprays. Directed foliar sprays are more cost-effective than basal sprays for controlling woody competition that is less than 6 ft. tall (Thomas and others 1989). Directed foliar sprays are usually applied with a backpack sprayer fitted with a spray wand equipped with a full cone, flat fan, or adjustable cone spray tip. Spray guns attached to the backpack unit with narrow flat-fan tips are also used by some applicators. Backpack mistblowers are another means of applying foliar sprays (Garrett and others 1989). The spray is applied to the target foliage, being sure to cover the growing tips and wetting the leaf surfaces without drip.

Herbicides labeled for directed foliar sprays for site preparation, that are not restricted to "conifer" reforestation, are:
- Accord and Roundup
- Garlon 3A and Garlon 4
- Tordon 101 and Tordon K
- 2,4-D and Weedone 2,4-DP

Tank mixes of these products will usually be more effective when treating mixed species (Johnson 1987; Shiver and others 1990, 1991). The comparative efficacy of most of these products when applied singly as foliar sprays at various timings have been reported, except the Tordons and 2,4-D (Miller 1990b). In general, the most effective timing for most species was found to be from mid- to late-summer. Arsenal Ac was also tested and found to have the most broad-spectrum control, but it is only labeled for conifer site preparation. Care should be exercised that at least 6 months lapses between application and planting when using Tordon.

Basal Sprays. Basal sprays are more costly than directed foliar sprays for controlling the same sized woody plants (Thomas and others 1989), but basal sprays can control trees larger than 6 ft. tall and can be applied in the late dormant season resulting in less unsightly brownout than foliar sprays. Labeled herbicides that have broad-spectrum control are Garlon 4 with no soil activity, and Access, Chopper, and Chopper RTU with soil activity. Chopper RTU is applied undiluted while the other products are mixed with oil and/or a penetrant for bark applications.

Full Basal. Full basal treatments require that the lower 12 to 20 in. of target hardwood stems be completely wetted with the spray mixture on all sides. A backpack sprayer is used with a wand or spray gun fitted with a narrow angle flat fan, cone, or adjustable tip. Herbicides are used that are soluble in oil and mixed at percentages specified on labeled products, usually less than 10 percent.

Streamline Basal. Streamline basal treatments can control many woody plants including hardwoods up to 2 in. d.b.h. (Miller 1990a). Trees of susceptible species up to 6 in. in diameter can be controlled. Treatment of small hardwoods that are less than 2 in. d.b.h. results in the most control.

To apply this treatment, a backpack sprayer is used with a spray gun and a low-flow (0.1-0.2 gallon per minute (gal/min)) straight-stream spray tip. Also, a narrow-angled tip can be used, such as 15° and 0.1 gal/min. For controlling herbicide output to prevent waste, a pressure regulator is needed to maintain pressure below 30 lb per square inch (lb/in.^{2}). At these pressures, an effective reach of 9 ft. is possible while bark splash is minimized. Sprayers with diaphragm pumps will maintain about 30 lb/in.^{2} with slow, steady pumping.

The most commonly used mixture for streamline application includes Garlon 4 at 20 percent, a penetrant at 10 percent, and a carrier such as diesel fuel or mineral oil. This mixture is clear when made correctly, while a white cloudy liquid or gel will form if even a small amount of water is present. No amount of water should be in the sprayer or mixing container. Make sure that all water has been drained from the sprayer, the pump has been pumped dry, and the sprayer has been rinsed and pumped with mineral oil or diesel before filling with the mixture.

For treating stems that are less than 2 in. d.b.h., apply the stream of spray up-and-down single stems for about 6 to 8 in. or as a 2- to 3-in.-wide band across multiple stems. Direct the spray stream at a point about 6 to 24 in. from the ground to smooth juvenile bark. Stems that are beyond the juvenile stage, thick barked, or near 3 in. in diameter require treatment on both sides, unless they are susceptible species. Back and forth bands can also be sprayed on larger stems.

Applications are usually made in late winter and early spring when leaves do not hinder spraying the stem and the effectiveness for many species is maximum (Pancake and Miller 1990). The best application time will depend on the herbicide, species, and location. Avoid applications on hot days if an ester formulation, such as Garlon 4, is used because crop injury may occur from vapor drift.

Broadcast Applications by Helicopters and Ground Sprayers. Herbicides labeled for broadcast applications prior to planting hardwoods are:

- Accord and Roundup
- Garlon 3A and Garlon 4
- Tordon 101 and Tordon K
- Oust (herbaceous plant control)

The best control will be obtained by using mixtures of these products if there is a mixture of target species on a site (Johnson 1987; Shiver and others 1990, 1991; Seifert 1990a). Oust can also be mixed with these herbicides without decreasing their effectiveness while increasing herbaceous control (Jones and others 1986). However, the most effective mixture for controlling a specific species mix is still up for conjecture, requiring the user to consult local extension specialists and knowledgeable managers. When competition is essentially only one species, then one herbicide may be best. For controlling sugar maple (*Acer saccharum* Marsh.), Garrett and others (1989) reported that Tordon 101 as a 20-percent solution was most effective of the 11 herbicides tested using a mistblower.

These herbicides can be applied by both aerial and ground sprayers. Aerial broadcast applications are commonly used on tracts of 50 acres or more, because of improved coverage and costs compared to ground applications. Professional aerial applicators generally use helicopters with spray systems equipped with microfoil booms, thru-valve booms, raindrop nozzles, or other devices to assure accurate applications with a minimum risk of off-site drift to neighboring lands. Managers should verify the accuracy of calibration before application. Herbicide mixing procedures, especially in batch trucks, should be examined and even tested for thoroughness, which can be performed by using electrical conductivity with Accord mixtures (Lautenschlager and Schaertl 1991). Pumping the mixture three times through the system can also assure adequate mixing. The land manager or owner also has responsibilities for preparing the site for aerial treatment, such as felling tall snags, heliport construction, and marking boundary lines that are visible from the air.

Broadcast site preparation treatments are also conducted with various types of tractor sprayers. Boomless cluster nozzles, manifold nozzles, and mistblowers mounted on either rubber-tired tractors and skidders or track-type tractors are used on sites with flat or gently rolling terrain. Applicators can now use computerized sprayer control systems on their tractors that automatically maintain the proper rate on terrain where ground speeds vary, but these require calibration that should be verified by the manager. For treatment of small regeneration areas, hose-reel sprayers mounted on trucks or tractors are also used.

Broadcast herbicide applications are often followed in 8-12 weeks with a prescribed burn to reduce standing and down woody material for better planter access. Burning does not always increase hardwood control (Minogue and Lauer 1992) and can volatilize site nitrogen, as previously discussed. Chopping is also being increasingly used after herbicide spraying in pine culture, with and without burning, to improve access and the ease of subsequent operations.

Control of Problem Plants During Site Preparation. Some of the problem weeds that can hinder or prevent plantation establishment are hayscented fern (*Dennstaedtia punctilobula* L.), New York fern (*Thelypteris noveboracensis* (L.) Nieuwland), japanese honeysuckle (*Lonicera japonica* Thunb.), kudzu (*Pueraria lobata* (Willd.) Ohwi), trumpetcreeper (*Campsis radicans* (L.) Seemann), grape (*Vitis* spp.), multiflora rose (*Rosa multiflora* Thunb.), privet (*Ligustrum* spp.), and eastern redcedar (*Juniperus virginiana* L.). A summary of herbicides for treatment includes:

Hayscented and New York ferns. Oust alone (1-2 oz/acre) or in a tank-mix with Roundup (1 qt/acre) applied between early July and early October (Horsley 1988, 1990). The timing of Oust for site preparation can influence the damage on other desirable hardwoods (Horsley and others 1992). McCormick and others (1991) in Pennsylvania on poorly drained soils found that fall applications of Oust at 2 and 4 oz/acre alone or in combination with Roundup at 1 qt/acre had no effect on germination of northern red oak (*Quercus rubra* L.), but did increase first-year mortality by 14-16 percent and reduced second-year height growth by 14-23 percent.

Japanese honeysuckle. Escort at 1 oz/acre applied May to August or Roundup at 0.75-percent solution applied September to October (Edwards and Gonzalez 1986, Regeher and Frey 1988, Schmeckpeper and others 1987).

Kudzu. Tordon 101 at 1-2 gal/acre or Tordon K at 0.5-1 gal/acre applied June to September both in year 1 and repeated with half the rate in year 3, with spot cleanup as needed and a 6-month wait before planting after last application (Miller 1988). Eradication on the site is needed before planting.

Trumpetcreeper. Roundup at 4 qt/acre applied July to September (Pyle and Krueger 1984).

Grape. Smith (1974) summarized screening trials and recommended basal bark sprays (lower 12-18 in.) in oil mixtures using 2,4-D ester (many brand names) and Weedone 2,4-DP at labeled rates and cut stump treatments using water mixtures of Tordon 101 (50-percent solution) and Roundup (20-percent solution) and undiluted Pathway (Tordon RTU, 101R), all applied early March or mid-September.

Multiflora rose. Roundup in a 1-percent solution or Garlon 4 in a 0.5-percent solution using summer or winter applications (Bhowmik and Germond 1987).

Privet. Arsenal AC in a 1-percent solution and surfactant sprayed in mid-summer.

Eastern redcedar. This species is not a basal sprouter, so cutting near groundline is effective. For large trees, foliar spray with Tordon K at 0.25-percent solution in a 1-percent diesel oil-water emulsion, wait 3-4 weeks, and ignite crown (Stritzke and others 1991).

These species must be nearly completely controlled or eradicated from a plantation site or the remaining plants will spread quickly.

SITE PREPARATION ON OLD FIELD SITES

The use of disking and subsoiling should be considered for improving soil conditions and competition conditions before planting oaks on abandoned fields and pastures (Malac and Heeren 1979). Disking treatments will improve planting operations if performed correctly and often promote annual herbaceous plants that are more effectively controlled with herbicides than are perennial plants. Disking should be to a depth of 8 in. and should be done in strips along the contour to reduce the chance of soil erosion. Unfortunately, disking can aggravate wet-weather planting the following spring. Subsoiling or ripping can be used to break up plowpans that are common to these sites.

Part of the decision to use tillage treatments must consider whether the site is designated as wetlands and whether the tillage practice would be considered "sod busting" that might jeopardize participation in USDA-sponsored farm programs.

For controlling pasture grasses and/or forbs before planting, late-summer applications of Roundup can be applied broadcast or in bands to form planting rows. Only Roundup appears specifically labeled for this situation. Rates of 3-5 qt/acre will be required to control established sod, and even then complete control cannot be expected. A prescribed burn in early summer, before the Roundup applications, can clear standing dead grass parts to improve herbicide efficiency. Also, mowing can be used to improve access and allows better spray coverage by reducing vegetation to a more uniform height. If mowing is done before a herbicide treatment, wait for 4-6 in. of weed regrowth before Roundup applications.

HERBACEOUS WEED CONTROL IN YOUNG OAK PLANTATIONS

Erdmann (1967) noted the benefits of herbaceous weed control on red oak establishment in old fields using Princep 4L at 1 gal/acre applied at the time of planting. Disking prior to spraying was found to enhance control. Erdmann, in the same study, and others (von Althen 1972, Wendel 1980, Nix 1989) have reported that black plastic and cardboard mulches are ineffective for herbaceous weed control with oak establishment and can harbor rodents. Erdmann reported that plowing and disking failed to stimulate rapid height growth of oak seedlings, but mechanical site preparation was a prerequisite to satisfactory weed control when using simazine (Princep). For sandy soils, he recommended applying 2-2.5 lb active ingredient/acre, although this use is no longer labeled.

Numerous screening studies have identified Oust, Princep, and Roundup (Accord) to be effective for herbaceous weed control when planting oaks, with the addition of atrazine having inconsistent results (Kosinski and Holt 1985; Wright and Holt 1985; Seifert and Holt 1985; Jones and others 1986; Seifert 1989a, 1989b, 1990b). Crop-tree injury usually increased with increased rates. Several of these studies also showed that Arsenal, as yet not labeled for hardwoods, held promise for herbaceous weed control with minimal oak injury. Seifert (1989b) after testing 11 herbicides/combinations applied for 2 consecutive years in southern Indiana, found that Oust provided the best weed control and least damage to northern red, white (*Q. alba* L.), bur (*Q. macrocarpa* Michx.), and black oak (*Q. velutina* Lam.) when applied at 1, 2, 4, and 8 oz/acre. Subsequent tests found that 4 and 8 oz/acre were too high and could result in stunting and mortality (personal communications with John Seifert). Wright (1986) studied pre-plant spring herbicide applications for site preparation for red and white oak plantings on old fields with forbs, grasses, and semiwoodies and found combinations of Roundup and Princep to be costly but effective while Oust was partially effective but released broomsedge. Unfortunately, resistant species (like broomsedge) or mid-summer annuals often recapture the treated area when effective herbaceous control is achieved, requiring the use of Roundup spot treatments with shielded spraying.

Two greenhouse studies have indicated that Oust inhibits the emergence and principally root growth of northern red oak (Sam and others 1986, Shipman and Prunty 1988), but the height growth of surviving seedlings was significantly increased. Similarly, Barnes and others (1990) have shown that Oust reduces root growth potential of loblolly pine (*Pinus taeda* L.), but it is still widely used for pine release because of eventual growth stimulation through competition control.

Sam and others (1986) found that of the preemergent herbicides tested, only Oust performed equally well on bare soil or forest litter. Therefore, applications to bare soil are not needed with Oust as has been required with Princep applications.

Two herbicides commonly used for establishing hardwoods have questionable registration at this time. In 1987, the use of Princep (simazine) for establishing forest plantations was removed from the label, although the product is still registered for Christmas trees, nurseries, and shelterbelts. Also, the use of atrazine is limited on labels to conifer establishment, which appears to make use in hardwood establishment the responsibility of the user with no recourse for product performance or crop damage. This interpretation may vary by State.

The use of repeated disking or mowing as a substitute for herbicide applications for herbaceous weed control has not been fully tested. Zutter and others (1987) reported that repeated herbicide applications were more effective than repeated cultivation for sweetgum (*Liquidambar styraciflua* L.) and green ash (*Fraxinus pennsylvanica* Michx.), because the inter-row vegetation was not controlled by cultivation. Malac and Heeren (1979) presented plantation establishment guidelines for hardwoods that stressed at least 2 years of frequent disking for competition control. The cultivator disks were designed to cast a mound of soil against the row of trees to smother the weeds within the row. Kennedy (1981) reported that 4 years of repeated cross disking on a clay soil with severe herbaceous competition enhanced diameter growth of Nuttall oak (*Q. nuttallii* Palmer) 240 percent over checks, while repeated mowing was not different from the check. When comparing cultivation with herbicide control, it is recognized that surface evaporation from cultivated soil is greater than from soil covered with herbicide-controlled vegetation acting as a mulch. However, preemergent applications of herbicides, because of their timing, may not result in a mulch of dead vegetation either. Also, the bare ground caused by either cultivation or herbicides will soon be revegetated to some degree.

Herbicides for Herbaceous Weed Control

Oust. At present, Oust is labeled for herbaceous weed control at 1-2 oz/acre after transplanting (not seeding), specifically for northern red oak, white oak, and chestnut oak (*Q. prinus* L.). The lower rate is used on coarse-textured soil. The efficacy of Oust on certain species is presented in table 3.

1. Oust is best applied as a preemergent herbicide (before weeds emerge).
2. Oust is not recommended for use on poorly drained or marshy sites, but it may be used where hardwoods have been planted in beds.
3. Application should be made at the time of tree planting or within 2 weeks of tree planting, in the spring before planted seedlings leaf out.
4. Seedling injury can occur if the planting slit is not fully closed and if bud break has occurred. Injury also can occur if heavy rainfall occurs after application and root growth has started.

Simultaneous seedling planting and spraying can be used with a simple spray attachment to the planting machine. Three years of herbaceous weed control have been recommended for hardwood establishment on old fields in Indiana by Wright and Holt (1985). Even though mixtures of atrazine and simazine have been in use for many years, they are no longer labeled specifically for hardwood establishment.

Table 3—Weed species usually susceptible to preemergent application of Oust at 2 oz active ingredient/acid equivalent

Susceptible	Moderate	Tolerant
Ragweed	Panic grasses	Broomsedge
Fescue	Goldenrod	Bermudagrass
Horseweed	Dogfennel	Nutsedge
Ferns[1]	Bahiagrass	Morningglory
Burnweed	Johnsongrass[1]	Woolly croton
Boneset	Pokeweed	Tropic croton
Sunflower		Trumpetcreeper
Poorjoe		Sicklepod
Dewberry[1]		Cocklebur
Vetch		Lespedeza
Geranium		Wiregrass
Golden weed		Plumegrass
Sweet clover		
Crabgrass		
Brome		

[1] Controlled only partly in preemergent or early postemergent applications to seedling plants, not established perennials.

Fusilade and Vantage (formerly Poast). Two herbicides that can be used for controlling only grasses are Fusilade and Vantage. (Vantage is a ready-to-use, weaker formulation of the herbicide Poast.) They are expensive products to use and both require up to two applications for controlling perennial grasses. Neither control broadleaf forbs or nutsedge. Fusilade is generally considered safe for over-the-top applications on all hardwood and conifer seedlings, while the phytotoxic effects of Vantage are assumed to be the same. Grasses must be small and tender for over-the-top applications. Fusilade is applied at 32-48 oz/acre with a nonionic surfactant and Vantage is applied at 35-61 oz/acre. Both can be applied only by ground application, using label-specified equipment.

Application Methods for Herbaceous Control

Herbaceous weed control can be accomplished using broadcast, band, or planting spot applications. Band applications are possible only when planting rows are well defined and wind conditions permit spraying well-defined bands. Banded or spot applications cost considerably less than broadcast treatments since only a part of the area is treated, while only small losses in pine growth and survival occur when bands or spots exceed 3 ft. in width or diameter relative to broadcast applications (Dougherty and Lowery 1991, Yeiser 1992). However, growth response increases in proportion to the area treated and reinvasion may be quicker with spots and bands (Dougherty and Lowery 1991). Initial growth retardation in the first year due to toxicity by some herbicides is overcome, resulting in a positive growth response by age 2-3 for both oaks and pines (Wright and Holt 1985, Yeiser 1992).

Broadcast applications can be made by backpack sprayers, tractor sprayers, or helicopters (Oust only). Banded treatments are applied using backpack, all-terrain vehicle (ATV), or tractor sprayers. Backpack sprayers treat one row at a time while machine sprayers can treat two or more rows using a boom with spaced nozzles. Bands usually range from 3 to 6 ft. wide. Precise mixing and application are essential for successful treatments.

To apply banded treatments, the boom or spray wand is fitted with a wide-angle, flat-fan tip, such as 80° or 110°, with flow rates of about 0.2 to 0.3 gal/min or two narrow-angle tips per row. When using a single wide-angle tip per row, a special flat fan tip that is "even" will increase control on the edges, compared to a regular flat fan that applies less herbicide on the edges. Also, flood tips are commonly used for banded applications, because one tip can apply a 3 to 5 ft. band. Wide angle or multiple tips are used to minimize the wind influence by having the tip close to the ground. Tip arrangements should be selected and arranged to assure even distribution across the band while minimizing rates around the planted seeds or seedlings. Thus, two tips can be positioned on either side of the seedling where the overlap is minimal to lessen the rate applied directly to the seedling.

Pressure regulation and a constant nozzle height and ground speed are needed to maintain uniform application rates. Use a pressure of 5 to 15 lb/in.^2 to give large droplets with reduced drift. The low flow rates from low pressure operation also permit more acreage to be covered per fill-up, adding to the efficiency of the operation. Special "extended range" or "low pressure" tips are designed especially for low-pressure applications. A pressure regulator is necessary to maintain low pressures with backpack sprayers as well. Some backpack sprayers can be set at the desired pressure while others rely on the installation of regulators in line or on the wand.

Many types of sprayers can be modified to apply banded herbaceous weed control treatments in plantations. One increasingly common machine is a four-wheel, ATV equipped with a sprayer. ATV and tractor sprayers can be equipped with sprayer control systems, with ground speed sensing. Sprayer control systems can maintain a constant application rate over a wide range of operating speeds (Miller and Mitchell 1988).

Spot applications must be used when planting rows are not well defined. Spot applications can be made with the above banding procedure using a backpack sprayer with some change. Mainly, the sprayer is turned off between seedlings as the applicator follows the rows. The sprayer is turned on about 1.5 to 2.5 ft. before the seedling and shut off at the same distance past the seedling. Thus the same tips, pressure, and calibration can be used. The applicator must still maintain a constant walking speed while spraying each seedling if the rate is to be constant.

Full cone tips, with flow rates from 0.2 to 0.4 gal/min, can be used to apply circular, tree-centered spots using a backpack sprayer or spotgun. However, full cone tips with these low flow rates produce very fine droplets that are easily blown by wind. An adjustable cone nozzle produces large droplets, but these droplets are too large to ensure uniform coverage of preemergent herbicides. Thus, it is difficult to achieve good results with full cone tips.

RELEASE AND THINNING

Inevitably release treatments will be required in oak plantations as partially controlled woody plants and new immigrants appear. Although research has begun to find effective over-the-top selective release treatments, it may be some time before successful treatments are identified and developed (Pham 1987).

Mixed results for oak release have been reported, but the variable results are probably due to ineffective control and the initial vigor of the released oaks. Wendel and Lamson (1987) concluded that rapid resprouting of cut-only release treatments nullify any benefit. Russell (1974) studied planted northern red oaks treated at 6-7 years in the Cumberland Plateau and found that woody competition clearing, once or continuously for 3 years, showed improved diameter growth, but not height growth after 3 years. Nix and Cox (1987) studied cherrybark oak (*Q. falcata* var. *pagodifolia* Ell.) plantings (2-0) and found that seedlings released in 3-4 ft. radius spots using Roundup directed sprays late in the second year did not grow better than unreleased trees. In a subsequent study, Nix (1989) reported significant release response to the same treatment on the same crop species, but released in the first year. Woodrum (1982) studied cherrybark oak in South Carolina and found that glyphosate release spraying caused decreased height growth (suspected drift) but increased diameter growth in the growing season of treatment.

As summarized in the introduction, diameters are influenced more than heights by competition reduction treatments, as also reported in these release studies. Also, release treatments must be applied at a very early stand age to ensure a response. Release should be applied in year 2 and repeated as needed to control invading arborescent hardwoods. Often, past the second year, the costs of control increase geometrically. Release treatments that treat greater than a 3 to 5 ft. diameter spot around the seedling should also be more effective but obviously will cost more. Sprouting clumps and tree species with rapid juvenile growth should be the primary control targets.

Roundup is the only herbicide that is currently labeled for "postdirected sprays" on "silvicultural sites." A 2-percent solution should be sprayed to cover the foliage of target woody competitors while preventing spray solution on crop foliage. To minimize crop seedling damage, a shield cover can be placed over the nozzle to help prevent drift. Also, applications should only be made during times of low wind. Drift control agents can be added to the spray mixture, but their addition can possibly lessen control effectiveness. Herbicide damage to crop trees can nullify any release response.

Release by directed sprays will only be feasible when target plants are less than 6 ft. tall and are species susceptible to Roundup. Garlon 3A, Garlon 4, and Arsenal AC could legally be used for directed sprays, but since the label specifies such treatments only for conifer release, the user would accept all liabilities of oak seedling damage.

Basal sprays with Garlon 4 in oil carriers can be used for release treatments, but crop-tree damage can occur from volatility when treating on warm days. Thus, winter applications in January and February are preferred. For larger competitors, cutting and stump treatments with Roundup and Garlon 3A are labeled uses, but crop-tree mortality may occur due to root grafts and root exudation and uptake.

Thinning can be important in the production of quality hardwood logs, and thus herbicides may play a critical role for precommercial thinnings and preventing resprouting of commercially thinned oaks. Both directed foliar and basal sprays could be used for precommercial thinnings. The systemic activity of herbicides will have to be tested to identify herbicides suitable for thinning sprouting clumps so as not to injure the selected crop sprout.

FUTURE REGISTRATION OF HERBICIDES FOR HARDWOOD MANAGEMENT

All herbicides used in the United States must be registered by the Environmental Protection Agency (EPA) as specified in the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and its amendments. To develop a new herbicide requires years of extensive scientific testing on the product's chemical properties, efficacy, and mammalian and environmental toxicology, after formulation development has been achieved. Costs of developing, testing, and registering a new herbicide presently exceed $30 million.

A unique requirement for pesticides registered for "forest use" is the environmental fate study, whereby the active ingredient and byproducts (metabolites) are tracked through a watershed application until dissipation below detection limits is documented in plants, soil, and water. This study alone now costs about $500,000 for a single test. Herbicide companies must then plan to recapture this investment plus profit, before embarking on a full "forest use" registration. Obviously, for products with good conifer tolerance and broad-spectrum control, this investment is justified, and over the past 15 years there have been numerous new herbicides registered accordingly. Unfortunately most of these herbicides are for controlling hardwoods, not establishing them.

Some herbicides, such as Fusilade and Vantage, are being used in forestry, especially for hardwood culture, under the categories of "noncrop areas" and "tree farm" without having an environmental fate study. It has been verbally conveyed by EPA that this procedure will be permitted as long as the herbicide is not used for broadcast applications in site preparation. Perhaps other herbicides presently registered for other crops can gain use in hardwood culture in a similar manner.

The registration process offers three other avenues for gaining labeled herbicides required for hardwood culture. First, herbicide companies could be requested to extend their existing forest use registrations of "site preparation herbicides for conifer culture" to include uses in hardwood culture. Tests of the residual activity of site preparation herbicides, like Arsenal Ac, would have to be performed and appropriate waiting periods between application and planting or seeding be specified on the label, to manage the liability risk. Second, shielded applications could be specified for nonselective herbicides for use as hardwood release treatments. This is underway with the Accord label, with promises to have shielded applications specified on the next label edition.

Perhaps the quickest way to gain registration is though the provisions in FIFRA for Special Local Need registration. Under Section 24(c) of FIFRA, a State may register any federally registered pesticide to satisfy special local needs, provided that (1) registration for such use has not previously been denied or canceled by

EPA, and (2) a food tolerance (safe levels in food), if required, has been established for the proposed use. In forestry the food tolerance would not be required. This "24(c)" registration process has been used for forestry herbicides, the most notable being for Oust in Indiana that led to a Federal supplemental label.

Going further back in the development process, some herbicide manufacturers have begun greenhouse screening on woody plants soon after newly synthesized molecules show promise on major crops and weeds. In the recent past, products suitable for forestry were only identified by happenstance during field screenings performed by company researchers in the "specialty products" areas—forestry being one of these. Still, it is most often the responsibility of "minor use" industries and government agency researchers to identify and develop the use of herbicides from those labeled for general agriculture or rights-of-way. Perhaps herbicide manufacturers can in the future be encouraged to identify those test products that demonstrate selectivity among hardwood species during these early screenings. This will probably be the only way that broadcast oak release herbicides can be developed. Of course, specific herbicides will only be developed when hardwood plantings are being made on a sizable enough acreage to justify this intensity of initial screening.

PUTTING IT ALL TOGETHER

Only with effective cultural tools can intensive oak culture become an affordable reality. Much greater research effort is required to develop these tools. Another effort will be required in sharing what works and what does not work—thus the importance of these Proceedings. The tools must be reasonably priced, which means that the market must be large enough for economy of scale in manufacturing, registering, and marketing. This will take time in the early stages as market size grows with continued success as well as good communication of cultural needs to entrepreneurs interested in this market. The implementation of new tools will require an added degree of technical sophistication by managers to be able to use new methods properly, such as modern herbicides. Integrated establishment systems, combining these tools, will need development and testing. The demand for quality oak wood will drive this development, but timely contributions from research, extension, and manufacturing will all be required.

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Collection and Care of Acorns

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ABSTRACT

The biological characteristics of acorns present acute problems in the collection and care of these single-seeded fruits. Indices of maturity are not complicated, but they must be rigorously followed in collection operations. Acorns collected too soon before physiological maturity will seldom germinate normally. Another critical factor is the high natural moisture content of acorns and extreme sensitivity to desiccation that they exhibit when dried only slightly below these high moisture levels. Maintaining this high natural moisture content is the key to maintaining good acorn quality, both in transport and in storage. High moisture contents prohibit sub-freezing storage and ensure a rapid metabolism that requires adequate aeration. For species that exhibit dormancy, the recommended storage conditions of near-freezing temperatures and maximum moisture contents will substitute for stratification in most cases. For the most vigorous germination, however, these conditions must be balanced with good aeration.

INTRODUCTION

The fruits of the genus *Quercus* are single-seeded nuts (Olson 1974). The biological characteristics of these nuts are different from those of most seeds, and these differences present acute problems in the collection and care of these fruits. Oaks of the United States belong to a group of species called "temperate recalcitrants." They are "temperate" because they grow primarily in the temperate zone; they are "recalcitrant" because their seeds do not tolerate desiccation below a critical moisture content (approximately 25 to 35 percent).

Seeds of other species, which can be desiccated to below 10 percent, are called "orthodox," which means that they behave nicely when desiccated and survive long periods of storage under proper conditions. The "orthodox" group contains all temperate zone conifers, and many important hardwoods, such as ash (*Fraxinus* spp.), black cherry (*Prunus serotina* Ehrh.), yellow-poplar (*Liriodendron tulipifera* L.), sweetgum (*Liquidambar styraciflua* L.), and sycamore (*Platanus occidentalis* L.).

The purpose of this paper is to review the crucial steps in collection and care of acorns, and to present the best current recommendations on how to collect good acorns and maintain their quality. Every step of this process is heavily influenced by the moisture relations and recalcitrant nature of acorns.

MATURITY INDICES

Acorns should be collected when they are fully mature and not before. Unlike multi-seeded fruits, such as pine or yellow-poplar, single-seeded fruits generally will not complete maturation after separation from the tree. The best maturity indices for acorns are (Bonner and Vozzo 1987):

1. Color of the pericarp.
2. Ease of separation of acorns from cups.
3. Cup scar color.
4. Cotyledon color.

In red oaks the pericarps should have lost their green color and be primarily dark brown or black before collection. An occasional exception to this rule can be made for southern red (*Q. falcata* Michx.) and cherrybark (*Q. falcata* var. *pagodifolia* Ell.) oaks. Individual trees of these species may produce mature acorns with a greenish tint to their pericarps. In white oaks brown and black are also good mature pericarp indicator colors, but again there are exceptions. Acorns from certain trees of white (*Q. alba* L.) and swamp chestnut (*Q. michauxii* Nutt.) oaks may be fully mature when pericarps are still yellow or even a mottled yellow and green.

These color changes are related to moisture loss with maturation. In Mississippi, white oak acorn moisture peaks at about 65 percent in early September, then drops to between 50 and 55 percent at maturity (Bonner 1976). Water oak (*Q. nigra* L.) acorns in the same region exhibit their maximum moisture content in August (65 to 70 percent), which then decreases to 35 or 40 percent at maturity (Bonner 1974c).

When acorns are mature, their cups come away cleanly with only slight pressure. If attempts to remove the cups cause them to break apart and leave pieces attached to the acorn, then the acorns are not yet mature. This is a simple test to carry out when collecting from branches. Overcup oak (*Q. lyrata* Walt.) is an exception to this rule, as these acorns are disseminated with their enclosing cups attached. The cup tissue is full of small air spaces, which apparently allow the acorns to float and be spread by moving water.

In red oaks, the cup scars on mature acorns are "bright" in color. On acorns of southern red and cherrybark oaks the scars may be bright pink or orange when first exposed. These colors fade within a few days of cup loss, however, so many good acorns collected from the ground may not show these bright colors. This index is most useful in checking maturity of acorns still attached to trees.

The last test for maturity is to examine a cross-section of acorn for cotyledon color. Species with naturally high fat contents, such as water oak, should have dark yellow to orange cotyledons. A pale yellow or white cotyledon indicates immaturity. Species with low fat content, such as Shumard oak (*Q. shumardii* Buckl.) and all white oaks, should have creamy white or light yellow cotyledons. Immature coloration in these acorns is almost the same as that of mature acorns. The higher the fat content, the deeper the orange color of the cotyledons. Mature overcup oak acorns are 50 percent carbohydrate and less than 1 percent fat (Bonner 1974a), and have almost white cotyledons. Cutting acorns in half also provides an opportunity to assess insect damage in the field. If insect larvae are found in more than 25 percent of the acorns, then collection crews should realize that additional acorns may be needed.

POST-HARVEST CARE

Because of the recalcitrant nature of acorns, much acorn quality is often lost between collection and storage. Acorns must be kept moist to maintain good seed quality. They should be collected and transported in plastic bags or in containers that can be covered to reduce moisture loss, especially if extended travel in the back of trucks is required. The steps that are taken to inhibit moisture loss also can lead to the problem of overheating (Gosling 1989). Overheating must be avoided, especially when plastic bags are used. Acorns should be kept in the shade while awaiting transport, and during transport, trucks should be parked in the shade when not moving. If the weather is warm, dry, and/or windy, spray the acorns with water. These are small things, but they can help maintain seed quality. In our experience, a loss of 5 percent moisture can be tolerated, but additional desiccation can lower acorn quality. If acorns are dried too much during collection and transport, moisture can be easily replaced by immersing the acorns in water at room or cold-storage temperature (Gosling 1989). Immersion is, in most cases, a good practice, and it leads logically to cleaning, the next step in acorn care.

CLEANING

As soon as possible after collection, all acorns should be immersed in water. This procedure serves two functions. First, it allows removal of leaves, cups, other trash, and insect-damaged acorns that float. Sound, healthy acorns typically sink in water. The exception to this rule is overcup oak, whose acorns always float with their large cups full of air spaces. Second, immersion helps maintain that all-important high seed moisture.

If conditions are extremely dry when acorns are collected from the ground, many good acorns will float initially. Under such conditions, acorns should be kept in the water for up to 24 hours to elevate their moisture contents and allow sound acorns to sink. Acorns collected from wet conditions should separate easily at initial floating. One should always cut samples of "floaters" and "sinkers" to determine the effectiveness of flotation to remove bad acorns.

After flotation and removal of trash, the water should be drained away prior to storage. Insect control measures should be taken at this time. The two common methods of control are immersion in hot water (120 °F) for 40 minutes, and fumigation with methyl bromide or other recommended chemicals (Olson 1974). Both of these methods present considerable risk to acorns, and the best alternative may be to do nothing. Most infested acorns will be removed in flotation. The larvae do not attack intact acorns during storage, so infestation does not increase. Damage is further decreased when acorns are put into cold storage. The temperature change encourages larvae to emerge from the acorns to pupate, and they die in the bottom of the container. Additional larval emergence can be encouraged by moving the acorns from cold storage to room temperatures and back again. Larval feeding must destroy the embryonic axis to prevent germination, so damage solely to cotyledon tissue does not prevent germination and development of a normal seedling.

If acorns are to be sized, the separations should be done at this time. Most nurserymen do not size acorns, but increasing use of mechanical planting, both in nurseries and in direct seeding, may lead to a wider adoption of the practice. Round-hole screens that are used in air-screen cleaners may be used, especially for small acorns. Sizing can have advantages in nurseries through its effect on seedling uniformity. A positive correlation between acorn size and seedling size (height or leaf area) has been reported for (*Q. rubra* L.) (Farmer 1980), *Q. robur* L., and *Q. petraea* (Mattushka) Lieblein. (Kleinschmit and Svalba 1979).

STORAGE

Most seed managers do not like to store acorns over long periods, because their size requires large refrigerated storage space and because viability declines each year. Acorns of most red oaks can be stored for 3 years without critical losses in viability (Bonner 1973), while most white oaks can be stored only 6 months without complete loss of viability. One solution to the problem is to plant acorns in the fall immediately after collection and avoid storage. For some nurseries and conditions, this option is a good one for next year's crop. Short-term storage under good conditions between collection and sowing is essential to maintain good acorn quality, however, and many managers would like to store extra acorns for use 1 or 2 years later. Since good storage practices for both purposes require the same facilities and procedures, the recommendations are the same.

Acorns of red oak species should be stored with their moisture contents at 30 percent or higher in temperatures near, but above, freezing (34 °F to 40 °F). Airtight storage is lethal, so containers must allow some gas exchange with the atmosphere while maintaining high acorn moisture levels (Bonner 1973). Polyethylene bags with a wall thickness of 4 to 10 mils are good. For large quantities of acorns, storage can be in drums, cans, or boxes with polyethylene bag liners. Container tops and liners should not be completely closed; this will allow sufficient gas exchange. If water collects in the bottoms of storage containers, it should be drained from acorns intended for storage longer than over winter.

With proper care, many southern red oaks should maintain good viability for at least 3 years (table 1). We have had good success in our laboratory with water, cherrybark, and Nuttall oaks (*Q. nuttallii* Palmer), but less success with Shumard and willow (*Q. phellos* L.) oaks. Similar methods were used by Farmer (1975) for successful storage of northern red and scarlet (*Q. coccinea* Muenchh.) oaks, and by Suszka and Tylkowski (1982) for northern red oak in Poland.

With few exceptions, white oak acorns cannot be stored longer than over winter (4 to 6 months) without complete loss of viability. For over-winter storage, the same methods outlined for red oak storage should generally be used. Thinner polyethylene (1.75 mil) or cloth bags may be advantageous for white oaks because of a need for greater aeration (Rink and Williams 1984). Schroeder and Walker (1987) reported excellent results in storage of bur oak (*Q. macrocarpa* Michx.) for 6 months at 34 °F and 44 percent acorn moisture in sealed plastic bags. No information was given on the thickness of the bags. Any reduction in acorn moisture significantly decreased germination capacity and rate. Tests in our laboratory (table 2) have provided some rare successes with storing white oaks species.

Moisture content remains a crucial factor throughout storage. With acorn moisture levels above 30 percent and temperatures above freezing, respiration proceeds at a rapid rate. This process gradually decreases acorn dry weight, causing small increases in the percentage of moisture over time (table 1). Schroeder and Walker (1987) found no increase in bur oak moisture content over 6 months of storage, but Gosling (1989) reported that English oak acorn moisture contents increased as much as 5 percent over 6 months in storage. The loss in dry weight is why a static state of equilibrium between internal acorn moisture and the storage atmosphere, such as we find in orthodox species, is never reached for acorns. Approximate equilibrium moisture contents have been determined for a few species (table 3), but these probably change over long storage periods. Note that white oak has much higher equilibrium levels than the two red oak species. This is because starch, the major storage food in white oak, is more hygroscopic than lipid, the major storage food in red oaks.

Table 1—Germination and moisture contents of cherrybark oak acorns stored in polyethylene bags at 3 °C and 8 °C[1]

Original moisture content and storage period	Germination 3 °C	Germination 8 °C	Final moisture content 3 °C	Final moisture content 8 °C
	Percent			
24 percent moisture				
6 months	80	76	27	28
18 months	9	0	30	34
30 months	25	24	32	33
31 percent moisture				
6 months	99	99	34	34
18 months	99	96	35	35
30 months	81	71	36	36
33 percent moisture				
6 months	100	98	34	32
18 months	93	95	31	36
30 months	94	34	37	40

[1] Bonner (1973).

Table 2—Viability retention of various southern white oak acorns stored at 2 °C, high moisture content, and in polyethylene bags[1]

Species	Germination Original	Germination 6 mo.	Germination 1 yr.	Germination 2 yrs.
	Percent			
Q. alba, white	90+	7.0	- -	- -
Q. virginiana, live	96.0	- -	60.7	17.6
Q. muhlenbergii, chinkapin	91.3	- -	39.0	2.0
Q. michauxii, swamp chestnut	86.1	- -	65.1	2.0
Q. lyrata, overcup	- -	- -	95.8	- -

[1] Bonner and Vozzo 1987.

Table 3—Equilibrium moisture contents of acorns for three southern oaks stored under two conditions of temperature and humidity[1]

Species	Storage conditions 40-55% relative humidity 4-5 °C	 95% relative humidity 4-5 °C
	Percent	
Shumard oak	13	32
Water oak	17	29
White oak	37	50

[1] Bonner and Vozzo 1987.

Between 70 and 75 percent of total acorn moisture in water and Shumard oaks is in the cotyledons and embryonic axes, while the comparable total for white oak is only 58 percent (Bonner 1974b). White oak pericarps are thicker than those of red oaks, and they retain more moisture. Cup scar vascular openings are major conduits for moisture uptake (Bonner 1968). Recent experiments in our laboratory on acorn desiccation indicate that these openings comprise the key pathway for moisture loss also. As acorns dry, the proximal end of the cotyledons (just beneath the cup scar) loses moisture first. Unless the pericarp splits, as it does at radicle emergence, the embryonic axis and the cotyledon tissue surrounding it (distal end) is the last area to be desiccated.

One method tested successfully for storing Nuttall oak acorns solved the drying problem nicely. Johnson (1979) stored Nuttall acorns for 6 months in drums of water maintained at 34 °F to 40° F. Similar results were obtained for water and cherrybark oak acorns in our laboratory for 5 months, but longer storage periods of 17 and 29 months led to considerable loss in viability.

Germination during storage has always been a problem for acorns, although not as great a problem as some might think. Southern white oaks have so little dormancy that they will germinate on the tree in extremely wet falls, so it is no wonder that they germinate profusely in storage. There seems to be an inverse relationship between degree of dormancy and germination in storage among red oak species. The conditions recommended for storage are the same ones normally prescribed for pretreatment (stratification) to overcome dormancy. Epicotyls usually do not appear, but radicles emerge and can grow as much as 8 in. in storage.

Microorganisms kill many radicle tips in storage, and many more are broken when sowing takes place. Secondary radicle development occurs in oaks, however, and other radicles should develop. These secondary radicles may even form sort of a multiple taproot system. Broken radicles did not adversely affect seedling production in nursery beds of cherrybark and Shumard oaks in Mississippi (Bonner 1982). Barden and Bowersox (1990) obtained similar results with northern red oak in Pennsylvania, but there were strong family differences. The common and proper response by seed managers is to do nothing to prevent this early germination. Decreasing acorn moisture slightly during storage of California black oak (*Q. kelloggii*) is reported to reduce the sprouting, yet not harm acorn quality (Tim Plumb, personal comm.). This approach should be studied for southern oaks.

CONCLUSIONS

Acorns are the most difficult of all temperate zone American seeds to collect and care for properly. Most of the problems are related to the naturally high moisture content of these seeds and the need to maintain those moisture levels to maximize seed quality. Desiccation during collection and transport must be avoided; a 5 percent loss of moisture can harm acorn quality. Acorns of many species can maintain viability for up to 3 years if they are stored a few degrees above freezing with high moisture contents and some gas exchange allowed. If seed managers recognize the moisture considerations and plan for their impact, loss of acorn quality can be minimized.

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The Use of Tree Shelters and Underplanting for Oak Regeneration

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ABSTRACT

Supplemental planting of oaks has been a success in many cases. It has also been a dismal failure in many other cases. Since successful stands of oak regeneration are often difficult to obtain, supplemental planting could be a method for increasing the desirable component.

A new tool recently surfaced in the United States is called the British "tree shelter." Tree shelters have been used in Great Britain for several years with good success. Initial trials in this country show that tree shelters contribute to better survival and increased initial growth. They will not, however, make a tree grow on a rock. Learning how to use tree shelters to the best advantage is still evolving in this country.

INTRODUCTION

Oak regeneration is seldom easy. Forest Service silviculturists are concerned because in many stands the oak component is being lost, especially when the stand is cut (George and Fischer 1991). Also, unusually large losses of northern red oak have been recorded in certain areas (Tainter and others 1984). The lack of adequate regeneration is a serious concern along the Appalachian Mountains in the eastern part of the region and especially to the west in the Ozark and Ouachita Highlands, where hardwoods, especially the oaks, are a major component of many stands (van Hees 1980, Beck 1983).

Even-age management by clearcutting has been the treatment of choice for many Forest Service silviculturists during the past several decades. Clearcutting without planting often did not result in a desirable species composition. Planting oaks, until recently, also did not result in notable success. Pine and hardwood species, other than oak, usually are more aggressive and invade good quality upland sites. All of this, despite concerned efforts, has resulted in a net loss of oak as a component of most upland hardwood stands.

Successes with clearcutting (Zobel and Davey, no year), seed tree cutting (Johnson 1976), and shelterwood methods (Loftis 1983) have been recorded. Others have tried the different regeneration systems on the same site (Johnson 1984). In most cases, however, when natural regeneration has been successful it has failed to increase the amount of oak in the new stand (Clark and Watt 1971). The authors also suggest that oak regeneration is more likely to fail on good sites than on poor sites.

The purpose of this paper is to discuss underplanting and tree shelters as means of increasing oak regeneration. Information in this area is limited. The current ban on clearcutting and the "New Perspectives" concept of forestry has added emphasis to the technique of underplanting hardwoods, especially oak, on National Forests.

Successful planting of oaks in an understory has been accomplished in the Missouri Ozarks (Johnson and others 1986). The prescription is a four-step process:

1. Prepare the site by controlling undesirable vegetation.
2. Create a shelterwood.
3. Plant.
4. Remove the shelterwood.

Step one reduces competition from woody plants. Unwanted woody plants less than 5.08 cm d.b.h. are controlled by the application of registered herbicides. The techniques used can be basal spray, injection, or sprayed cut stumps.

The second step is the creation of a shelterwood with about 55 to 65 percent stocking based on Gingrich's (1967) stocking relations. If the stand is already understocked, little need be done. If it consists of cull trees that are not merchantable, this step can be combined with step 1. Johnson states: "The purpose of the shelterwood is to provide a uniform tree cover that permits a moderate amount of light to reach the forest floor without greatly stimulating the growth of woody and herbaceous competition." Some undesirable stock may need to be left to achieve the desired uniform shade condition.

The third step is very important. Large nursery seedlings, 1.27 cm diameter or more measured 2.54 cm above the root collar, should be used. Most nurseries do not grow a seedling this large in 1 year. However, 1-0, 2-0, or 1-1 seedlings can be used as long as the desired size is obtained. Root pruning, 20.32 cm below the root collar and top pruning 20.32 cm above the root collar, is recommended. The top pruning should be done within 2 weeks of planting to allow root growth promoting substances in buds to be translocated to the roots.

The fourth step requires the complete removal of the shelterwood and must be accomplished in the dormant season 3 years after planting. If necessary, stumps of undesirable species in the shelterwood cut should be treated after harvest.

This technique is applicable in other areas but the number of trees planted per acre, time of planting, and competition control will vary and must be adjusted to meet local conditions.

Johnson (1984) also compared the responses of planted northern red oak in clearcuts and plots thinned to 60-percent stocking. The study was conducted in the Missouri Ozarks. Planting stock was divided into four size classes: (1) large 1-0 seedlings (>60 cm tall); (2) small 1-0 seedlings (30 to 60 cm tall); (3) 1-1 transplant seedlings (>30 cm tall); and (4) 1-year-old container grown seedlings (>30 cm tall).

Shoots were clipped on one half of the trees in each size class. After three field growing seasons, the overstory was removed on half of the underplanted plots. After 5 years, average survival was 84 percent.

Johnson states that, "Overall, planted oaks grew faster in clearcuts than under partial cuts. But because competitors also grow rapidly after clearcutting, planted trees must promptly initiate rapid shoot growth after clearcutting. Clipped planting stock in the underplant-release treatment demonstrated that capacity during the two years after clearcutting; trees planted directly into clearcuts did not." The reason for this may, in part, be due to the greater initial root growth per unit leaf area of transplants over seedlings.

After 5 years in the field, the most successful trees were clipped 1-1 seedlings with initial shoot diameters (2 cm above the root collar) of 10 mm or more that were underplanted and subsequently released. However, undercut seedlings may perform as well as 1-1 transplants (Johnson 1989).

It is important that additional studies have also been installed and are in progress. Results have not been reported. The Ozark National Forest has installed an administrative study designed to help that forest determine the optimum amount of overstory density to maintain above planted northern red oak seedlings (Smith and others 1984). "The objectives of the study are to evaluate the growth of underplanted 2-0 northern red oak that are released from one of three overstory densities (40, 60, or 80 percent stocking) 3 years after planting. In addition, the effects of the following three levels of understory competition control will be evaluated: (1) none, (2) one pre-planting application of herbicide, and (3) one pre-planting plus one post-planting mechanical control treatment of undesirable plants. Planting stock will include fall- and spring-lifted trees. Within both classes of stock, the effects of shoot removal 15 cm above the root collar will be evaluated by comparing spring removal, fall removal, and no removal. Seed source will also be a variable in the study. Four local sources will be used to assure and account for some genetic diversity."

The technique of underplanting hardwoods, especially oak, is not widely used by silviculturists. When I queried the Forest Service silviculturists in Region 8, the response was negative. Over the years several forests and districts have tried underplanting oaks of various species with little success. Most referred me to the work being done by Paul Johnson in Missouri.

In the present climate of limited clearcutting on the National Forests in Region 8, underplanting certainly has a role to play. If the oak component is declining, underplanting may be the only method available to maintain the species in many stands. Silviculturists would be well advised to learn more about the technique.

TREE SHELTERS

Tree shelters are a relatively new tool in the United States. They were developed in Great Britain in 1979; therefore, the use in field situations has been short-term. Their use with hardwood trees is intended to increase survival, aid in establishment, and increase early growth. Tree shelters also provide protection from animal damage, herbicide applications, and offer some protection against mechanical and environmental damage—sun scald, wind, and ice (Potter 1991).

Tree shelters are transparent or translucent polypropylene plastic tubes, either round or square, of varying diameter and height, color, and design. They are generally secured to the ground with a wood or metal stake of appropriate length.

Several types of tree shelters are commercially available from both U.S. and European manufacturers. Tree shelters should not be confused with tree guards which are made from metal or plastic mesh and are only intended to provide protection from various animals.

The plastic shelter creates a mini greenhouse around the tree. Temperature ranges, humidity, and CO_2 levels are increased while light levels are lowered (Rendle 1985). This effect promotes survival and rapid juvenile growth for the oaks. Under normal unsheltered conditions, oak seedlings usually develop very slowly.

Tree shelters also can serve an important function in planting oaks and other hardwoods in urban areas. On these incredibly harsh sites they protect young trees from both human traffic and groundcare equipment (American Forestry Association 1989).

On extremely arid sites tree shelters have been used to protect against high winds and blowing sand. Moisture stress from drying winds was also reduced. Bainbridge (1990) reports, with mesquite in the Colorado desert, that after 90 days seedling survival increased from 0 percent in plastic mesh to over 80 percent in tree shelters. Average height growth after 90 days was 0 cm using plastic mesh and 40 cm using tree shelters.

Increased growth and survival, however, seem to be larger in Great Britain than in the United States. Tree species and climate apparently influence the potential of hardwood seedlings in a tree shelter (Windell 1991). Nevertheless, the impressive results from both survival and growth in Great Britain and initial tests in the United States cannot be ignored.

Early Results

After 3 years the mean height growth, in Great Britain, of sessile oak transplants in shelters was 142 cm compared with 45 cm in a mesh guard and 27 for unprotected trees. The average stem volume was 118 cm^3, 37 cm^3, and 19 cm^3, respectively. There was no difference in growth in a range of sizes of conical- and cylindrical-shaped shelters. An 8-cm diameter cylinder is large enough for sessile oak (Tully 1985).

In another study in Great Britain, Rendle (1985) states: "The results of a three year investigation into the effects of tube shelters on microclimate and the growth of oak (*Q. rubur*) compared with field conditions, showed the environment of tubes has an increased temperature range, lower light levels and increased humidity when the tree is in leaf. Trees grow faster in height in tubes compared with the open but do not differ in terms of total dry weight production. However, the distribution of dry weight between stems, branches, and roots does differ."

At this time, results of studies in the United States are limited, but there is sufficient evidence to proceed quickly in determining just what role tree shelters should play in hardwood regeneration and management.

Manchester and others (1988) report that, after 2 years in North Carolina, chestnut oak grew to an average height of 47.5 cm in shelters and 50.8 cm without; white oak was 46.3 cm tall in shelters, 27.9 cm without; and northern red oak was 62.2

cm tall in shelters, 12.7 cm without. The survival rate after 2 years for trees without shelters was 31 percent; for trees with shelters, survival was 94 percent for all species. Chemical control of vegetation was applied in a 0.6-meter circle around each seedling 2 months following planting.

A test in Michigan using tree shelters shows that, after 2 years in a clearcut, northern red oak grew 42.9 cm in height with shelters and 23.4 cm with no shelter (Lantangne 1990). After planting, seedlings were clipped 17.8 cm above the groundline. Tree shelters were then installed. In this test northern red oak seedlings planted in tree shelters were 40 percent taller than unsheltered seedlings after one growing season and 42 percent taller after two growing seasons. The average increment in total height due to sheltering trees declined from a factor of 2.4 times during the first growing season to a factor of 1.8 times during the second growing season. No mention is made of survival for the planted trees.

Early test results from the United States are impressive though not as dramatic as those from Great Britain. The benefit of increased survival of planted hardwoods, especially oaks, seems to be as important as the increased juvenile growth.

Other studies are being installed throughout the United States. More and more companies are manufacturing and selling shelters of different designs. As a planting tool, they are likely to be with us for awhile; but, like the old snake oil drummer harking loudly that his potion will make hair grow on a billiard ball, tree shelters will not make a tree grow on a rock. Their useful function in this country remains to be determined.

SUMMARY

Clear or white shelters increase success in planted shelterwoods or when used in an understory situation. Green or brown shelters, however, seem to be more environmentally acceptable to the public.

Tree shelters must be installed properly. They should be secured to a wood or metal stake which has been driven into the ground. The tree shelter, itself, should be pushed or driven into the loose soil about 1 in. deep at the bottom. If it isn't, the shelter will act as a chimney and cause the seedling to dry out. Tree shelters come in various lengths. An appropriate length should be used.

Public acceptance of tree shelters is still an open question. They are more acceptable if they blend into the background and are not planted in geometric patterns or straight lines. The plastic residue of the shelters, as they break down and become a part of the forest environment, may be a long-term problem. Some workers have proposed that the residue be picked up and hauled out of the forested setting. This would be an added cost unless different and more acceptable materials are found to construct the tree shelters.

The cost of tree shelters along with the cost of installation is relatively high per unit. Manchester (1991) reports of $2 to $3 per tree for total establishment on the Andrew Pickens Ranger District in South Carolina. Initial cost of the tree shelters may come down as more and more are manufactured and sold in this country. Also, the per-acre cost may be acceptable because less hardwood trees need to be planted if survival increases substantially as indicated in early tests.

Tree shelters definitely protect trees against deer and other browsing animals. The cost will probably be less than that of constructing deer-proof fence. Bears have destroyed small areas planted with tree shelters by knocking them down and tearing them into large pieces. Their presence seems to offend bears. Bluebirds and buntings may get into the tops of shelters and become entrapped. One manufacturer has devised a flexible polypropylene netting to place over the top of the tube.

Mulch mats and chemical weed control are more beneficial to seedling growth than fertilization alone when used in conjunction with tree shelters.

Pressure-treated and hardwood stakes can be used with tree shelters. The pressure-treated stakes will last longer in moist climates in the South.

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Summary Papers

Oak Regeneration—Where Do We Go from Here?

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ABSTRACT

Care has to be exercised when referring to the regeneration problems of oak. Special problems are encountered with the regeneration of northern red oak in the Southern Appalachians and the Central States, but many red oaks regenerate without limitation.

On upland mesic sites where yellow-poplar and red maple are strong competitors, procedures are available to determine whether the desired reproduction will be obtained or not. Advance oak reproduction (greater than 4 ft. tall) must be present at the time of the regeneration treatment for the desired oak component to be competitive. Control of the undesired vegetation is required if the smaller oak reproduction is to gain dominance.

There will be a continuing demand for quality oak timber; thus, the question is "who will be producing that timber?" I do not foresee forest industry contributing significantly to the resource base because of their commitment to fiber production. Also, I do not foresee the nonindustrial private owner making a conscious effort to regenerate the species due to the long rotation ages needed to produce quality timber. It, therefore, will likely fall the responsibility of the public sector to husband northern red oak to keep it from becoming the "California Condor" of the Eastern deciduous forest in future centuries.

INTRODUCTION

Fresh with a Ph.D. in forest genetics I was asked, some years ago, to prepare a paper on the genetics of the southern pines. Setting to the task, I did what I thought was a good job. Eager for a reviewer's comment, I asked the principal geneticist of Britian's Forestry Commission—who was visiting us at the time—for his assessment. Back came the reply: "You write a good paper but treat the subject as if the southern pines are the only pines in the world. You need to spend time outside the southern United States to learn the reproductive biology and silviculture of other pine ecosystems." That constructive criticism stung but, upon reflection, I set out to find a place to accommodate me. The choice was New Zealand, where I was employed by the New Zealand Forest Research Institute for 1 year. My job in that distant land was to increase seed production of Monterey pine (*P. radiata*) seed orchards.

Since New Zealand was (and still is) almost totally dependent upon exotic tree species for establishment of commercial plantations, and since the ink on my Ph.D. thesis was still wet, I arrived there with the hidden agenda of convincing the authorities to do away with monoculture, the top three species of which consisted of Monterey pine, Monterey pine, and Monterey pine. When I departed 1 year later it was I who had been converted. Even if catastrophe were to strike, the New Zealanders had determined that the benefits from intensively culturing Monterey pine were sufficiently greater over the second- and third-best exotics to warrant the extensive monoculture.

I cite this experience to suggest that the majority of the researchers and practitioners of oak management attending this symposium look beyond the Southern Appalachians and Central States to experience for themselves that the oak regeneration "problem" is not everywhere a problem. Research results obtained through the N.C. State-Industry Hardwood Research Cooperative[1] show that adequate oak reproduction has been obtained from east-central Mississippi (Bowling and Kellison 1983) to Florida (Leach and Ryan 1987) (Table 1), to Virginia (Heeren 1992, personal communication[2]). Despite the fact that the oaks identified in these research trials are predominately *Quercus laurifolia*, *Q. nigra*, and *Q. phellos*, they are oaks. They are highly desired as fiber species, and their fruit provides nutrition for a wide array of birds and animals, not to mention insects.

Table 1—Regeneration at 18 years following clean cut of a mature stand, with and without residual control, on a black-water river (Escambia River, Escambia County, Florida)[1]

Treatment	Oaks	Gums	MCS[2]	Elm	NCS[3]
	Stems per Acre (no.)				
Clean cut	1,296	141	50	35	613
Without residual control	664	11	2	37	375
Residuals excluded	639	2	2	36	374
	Volume per Acre (ft^3)				
Clean cut	1,221	134	29	35	169
Without residual control	978	213	12	67	124
Residuals excluded	710	17	12	4	94

[1] Data courtesy of Champion International, Cantonment, FL.
[2] Miscellaneous Commercial Species.
[3] Non-Commercial Species.

Oak regeneration, primarily of sprout origin, is also common in the high Piedmont Plateau and the foothills of the mountains on land of site quality less than 70 (50-year base) (Brenneman and Boyette 1978). There the species are primarily black, (*Q. velutina*), scarlet (*Q. coccinea*) and white (*Q. alba*) oak. In west-central Tennessee, chestnut oak (*Q. montana*) of site index 70 (50-year-base) dominates whole ecosystems.

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[1] The Hardwood Research Cooperative consists of 11 industrial and three public agencies with land holdings in 10 Southern States.

[2] Hardwood Research Forester, Union Camp Corporation, Franklin, VA.

Similarly whole ecosystems of oak, primarily of black, northern red, and white oak, dominate the forests of the Boston Mountains where site index only occasionally exceeds 80 (50-year base) (Graney 1983). Even though an objective of this symposium is to identify the scope of the problem, I caution us not to be so quick to identify oak regeneration as everywhere a problem.

Regionally, the lack of oak regeneration, especially northern red oak (*Q. rubra*) is a problem, as identified by Loftis (1990a, 1990b). However, those problem areas occur on high oak site-index (more than 70 feet, 50-year base) land, especially where yellow-poplar (*Liriodendron tulipifera*) and red maple (*Acer rubrum*) are competitors. It is to these sites that the remainder of this paper is committed.

The Demand

Quality red oak lumber has been in demand for furniture, barrel staves, building beams, farm implements, wood fuel, and other uses since the time of the European settlers. Following World War II, oak strip flooring became highly popular and great demand was again made on the natural resource. That fad lost momentum in the late 1950's, as a result of wall-to-wall carpet that covered the floor of low-grade lumber or plywood. Another large drain on northern red oak began with the bicentennial celebration of the United States in 1976. Oak furniture became the item of choice, succeeding from pecan (*Carya* spp.) in the previous decades. In actuality, production of wood furniture inclusive of oak has been relatively constant over the past two decades, increasing from a base of 100.0 in 1972 to only 107.1 in 1990 (Nolley 1992). More significant, however, is the increase in the value of wood furniture imports during that period. Using the 1982 United States dollar as the base and adjusted for inflation, the value of imports increased from $288 million in 1972 to $1,949 million in 1990. In contrast, the value of domestic wood furniture shipments increased from $6,029 million in 1972 to only $6,455 million in 1990. These values correspond to an increase in the ratio of imports to domestic production from .05 in 1972 to .30 in 1990.

The conclusion from these statistics might be that the tropical rain forests have contributed greatly to the wood furniture industry. Until recently, when a hue-and-cry developed over destruction of the tropical rain forest, that conclusion would have been acceptable. However, the concept carries less validity when it is realized that the export of red oak logs from the United States has increased from 16,549 thousand board feet (mbf) in 1978 to 54,396 mbf in 1988. During that time, the price of Grade 1, 16-ft. logs increased from $161/mbf in 1975 to a high of $648/mbf in 1990, f.o.b. mill. The fact is that much of the log-price increase and much of the increase in wood-furniture imports are coming from logs that were exported from our shores.

The trends during the past two centuries and especially during the past two decades suggest that there will continue to be a demand for northern red oak, for quality timber and wildlife values as well as to ensure that the venerable species remains a component of the Appalachian, Allegheny, Northern Hardwood, Central Hardwood, and Boston Mountain forests. The question remains: "Who will grow quality hardwoods and especially who will grow northern red oak?"

The three major categories of landowners of the Eastern deciduous forest—nonindustrial private, industrial private, and public—have holdings that approximate a 70:20:10 ratio. Even with the high log prices I have cited, I do not see the nonindustrial private owner managing for northern red oak on any significant scale. Even if he is interested in regenerating the species, there will be reluctance to cut the timber until a family emergency arises or until the property changes ownership. And, then, there is always the question of economics. Not many of us, in the absence of an owned manufacturing facility, are willing to invest money in a project rife with potential disaster from fires, winds, insects, and diseases, that will mature in 60 to 120 years. Treasury bonds, even with the huge debt of the U.S. Government, are more attractive investments. Similarly, I do not see forest industry—especially those with pulp and paper as their objective—managing for the relatively long rotations required for the production of quality northern red oak timber. They are primarily interested in fiber to keep the huge pulp mills running, costing in excess of $500 million. If the private sector were solely responsible for ensuring the supply of northern red oak, this valuable tree species might become the "California Condor" of the Eastern deciduous forest (Fralish and others 1991).

That leaves the public sector with its 10 percent of the Eastern deciduous forest. Twenty years ago most of us would have concluded that the future supply of domestic quality hardwoods, inclusive of northern red oak, would be coming from public lands, primarily from the National Forests. Today, that assumption is very much in question. The demand being made by the public on the National Forests for purposes other than timber production, and the New Perspectives approach being taken by the USDA Forest Service (Salwasser 1991), will pretty much exclude that source of timber. If those concerns are not enough to stop the timber harvest on public lands, an endangered species such as the northern spotted owl (*Strix occidentalis*) or another ploy governed by legislation will be used to accomplish the purpose. At best, only selective forestry will be practiced on the National Forests. Evaluation of the land then will be measured by social values rather than by Faustmann's land rent values (Davis and Johnson 1987). As long as the timber can be obtained elsewhere, we will become a net importer of quality hardwoods and products from which they are made. Western Europe has been in this mode since at least 1970. One wonders what the alternative will be when other countries also decide that their timber is more important to them for production and social value than it is for export.

In the Meantime

Research has shown that northern red oak can be regenerated and made part of the succeeding stand on the high quality sites (site index 90, 50-year base for yellow-poplar) to which it is adapted in the Southern Appalachians (Loftis 1990a, 1990b). However, the success comes at great expense from control of yellow-poplar and red maple on sites where these species are common. The cause for these two species suppressing northern red oak, even when all were of equal size at time of regeneration or release, is unknown. However, it is speculated that the absence of ground fires and cattle grazing have contributed to the problem. Logic would suggest that many occurrences of fire, at periodic intervals, would be needed to control the earlier successional species of yellow-poplar and red maple while favoring northern red oak. Another probable cause for the demise of northern red oak at the expense of yellow-poplar and red maple is the loss of American chestnut (*Castanea dentata*) to chestnut blight (*Endothia parisitica*). Evidence shows that yellow-poplar was at a considerably lower frequency level at the time of the predominance of American chestnut. Whether yellow-poplar was held in check by an allelopath or another competitive effect of American chestnut, or whether yellow-poplar is an opportunistic species that has only filled the void created by the death of American chestnut, is a matter of speculation.

Many of us at this symposium are addressing the idiosyncracies of oak regeneration and subsequent stand development as if they were new phenomena. Not so!! One of the most noted naturalists in the history of our country, Henry David Thoreau, made detailed observations and notes about the difficulties of obtaining desired oak reproduction (primarily northern red and scarlet) following removal of the parent stand in which good quantities of oak were present. He also concluded: "The time will soon come when we shall have to take special pains to secure and encourage the growth of white oaks, as we already must that of chestnuts for the most part. The oaks will be so scattered that there will not be enough to seed the ground rapidly and completely" (Torrey and Allen 1962, page 1698). The time was in the late 1850's, and the area was the environs of Walden's Pond, Massachusetts.

The naturalist observed that (red) oak regeneration under pine stands (*P. strobus* and *P. rigida*) was greatly superior to that under oak stands. The seedling oaks under overstory oaks were fewer than under pines; roots of these were old and decaying, and the shoots slender, feeble, and more or less prostrate under the leaves. The roots were not as fusiform shaped, and only one-tenth as many would develop into a second-growth stand as would develop under a pine stand. He further concluded: "If you expect oaks to succeed a dense and purely oak wood, you must depend almost entirely on sprouts, but they will succeed abundantly to pine where there is not an oak stump for them to sprout from" (page 1709).

Going further, the naturalist concluded: "Methinks you do not see numerous oaks of all ages and sizes in an old oak wood, but commonly large trees of about the same age and little ones like huckleberry bushes under your feet; and so commonly with pine woods. In either case, if the woods are well grown and dense, all the trees in them appear to have been planted at the same time. For aught I know, I would much rather have a young oak wood that had succeeded from pines than one that had succeeded from oaks, for they will make better trees, not only because the soil is new to them, but because they are all seedlings, while in the other case the greater part are sprouts."

I conclude from these remarks, from personal experience, and from the results of numerous researchers (Beck 1980, Carvell and Tryon 1961, Loftis 1990a, Sander and Clark 1971) that regenerating an oak stand following removal of the parent oak stand on upland mesic sites can be done, but it will be time-consuming and costly. The only logical chance of immediate success is to favor those stands with advance reproduction (Loftis 1990a) or those with high stump-sprouting potential (Johnson 1977). Models have been developed to serve as guidelines for successfully regenerating oaks in the Southern Appalachians and the Central States by the above-named scientists, and in the Mississippi Delta by Robert L. Johnson, former Project Leader of the USDA Forest Service, Southern Hardwoods Laboratory. These and other models are in need of refinement which can only be satisfactorily accomplished from input of research results being regenerated by the likes of the scientists represented at this symposium.

I also conclude that efforts to cause oaks to succeed themselves on upland mesic sites is unnatural, and that a reduction in tree and stand quality, and in site degradation, as suggested by Henry David Thoreau (Torrey and Allen 1962) could be a result on marginal sites. The total or partial harvests used today for timber removal and stand regeneration are greatly different from what would have been encountered in the original stands where repeated low intensity fires and grazing were common phenomena, or where conflagrations or wind would have likely completely destroyed the forest cover. In those situations, species succession would likely have played a major role, preventing one species from succeeding itself to the exclusion of other species. The benefits from species succession are the prevention of site degradation and pest build-up. The forest manager can learn a lesson in this respect from the agronomist who refrains from planting the same crop on a given soil for more than 2 successive years even when the option exists to replenish nutrients that are removed with each annual crop, and even when integrated pest management could conceivably hold epidemic levels of pests at bay. Still, the value of regenerating a valuable crop such as northern red oak, for biodiversity, timber, wildlife, aesthetic, watershed, and recreational purposes, may more than offset the potential site degradation and pest build-up problems. Northern red oak could conceivably become to the Southern Appalachians what Monterey pine is to New Zealand!

Confusing Terminology

I have used the term "forest succession" in the above paragraph. The purist would take exception to that term, equating it to the concept of *relay floristics* as proposed by Clements (1916). *Relay floristics* presupposes that plant formations follow a progressive succession, from pioneering species to a climax or stable community. Unfortunately, it also presupposes that the pioneer community modifies the environment to allow for the succeeding vegetation stage (sere), and that sere modifies the environment to allow for the next sere, etc., until the climax sere is reached. In my simplistic way of looking at plant succession, I do not presuppose that one plant community modifies the environment for the second sere, etc. I do hold to the principle that one sere succeeds another, but all of the species of the different seres could either be present from the beginning (*initial composition floristics*, as proposed by Egler, 1954) or they could be located there by plant migration, over time, through various dispersal mechanisms and the resiliency of seed banks and vegetative propagules (Gleason 1926).

I am of the opinion that we are confusing ourselves, to say nothing of the public, by our adamancy for labeling forest ecology events. The public only wants to know that we are practicing good forestry, and that should also be our first priority. Let us quit being so sensitive, for example, about the neophyte advocating the use of selective harvesting which, to us, equates to high grading. The neophyte does not have high grading in mind; he only wants the forest to be harvested (if it is to be harvested!) in a way that does not destroy his vista. We have the options to sometimes avoid those confrontations. Let us exercise those options, where appropriate, and call it good forestry without confusing our potential adversaries with terminology we *ourselves* do not fully comprehend.

CONCLUSION

Northern red oak is a struggling species. If it is to be maintained, special effort, at a high cost, will be required to ensure that either advance reproduction is present before the canopy of the parent stand is opened to any significant degree, or that competiting species such as yellow-poplar and red maple are controlled enough to allow development of subadvance reproduction. Numerous procedures have been detailed at this symposium to determine the conditions on which northern red oak can be successfully managed. In addition to the regeneration, the best silvicultural practices will be required to suppress the competition, including the use of fire, herbicides, and hand weeding. Because of the cost of the exercise, the practice will largely be confined to public lands. Additional research is needed to determine the cause of poor early development of northern red oak when compared to other species.

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Oak Regeneration: A Summary

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A FINAL WORD

The oaks are a paradox. Under many conditions they reproduce themselves naturally in profusion. The genus has also been widely planted as an ornamental with great success. Yet, these Proceedings document that oak regeneration can be difficult to obtain. The purpose of the Symposium was to define trends and problems and to present the best available technology on oak regeneration. The purpose of this summary paper is to react to some of the observations, conclusions, and recommendations presented in the Proceedings. This paper will recognize consensus but will also point out exceptions and inconsistencies. Gaps in knowledge and lack of reliable procedures will also be briefly discussed.

The oak regeneration problem is recognized and described under two categories, natural regeneration and artificial regeneration. Natural stands of oaks have been observed under certain site conditions not to be regenerating. These failures in regeneration have been observed following an array of regeneration methods. The regeneration failures have ranged from almost complete loss of the oak component to a reduction in the relative dominance in the stand or the loss of one species of oak, when compared to the composition of the previous stand. The regeneration problem with oak plantations has been mostly one of slow growth of the oak seedlings following planting. Low early survival has also been an occasional problem. The general complaint, however, has been that we can get the planted oaks to live but we cannot get them to grow.

The oak regeneration problem has affected most of the oak species in the East and occurs throughout the entire Eastern oak forest. While the problem is reported to be widely distributed, both geographically and by species, the intensity of the problem is strongly associated with the quality of the site. The consensus in these Proceedings is that the difficulty of obtaining successful oak regeneration increases as the quality of the site increases. While some oak regeneration problems do occur on poor sites, e.g., plantation survival, the most severe problems have been reported on the very best sites.

The potential causes of the oak regeneration problem are apparent and are readily identified and described. However, it is much more difficult to determine and describe the specific actual cause of a particular oak regeneration failure. Causes of oak regeneration problems can usefully be separated into aggravating factors and limiting factors. A relatively long list of aggravating factors has been mentioned. These aggravating causes include flower production, acorn supply, seedling density, climate, insects, disease, animal depredation, fire, and flooding. However, there is consensus that the primary cause of general oak regeneration failure is the slow growth of oak reproduction relative to competing species. Even in plantations when competition has been eliminated, juvenile growth has usually been slow. The biological explanation as to why oak reproduction grows slowly even when released is an important subject covered in these Proceedings. A key statement suggests that oaks are not flexible and do not adapt well to a rapidly changing environment. Thus, increased supplies of light, water, materials, and space cannot be rapidly utilized. Similarly, saplings may not adapt to the adverse effects of sudden exposure to light and temperature extremes. Lack of flexibility, however, does not explain slow growth in plantations. The best explanation of poor plantation performance is that the planted oaks have had shoot/root ratios that were too high.

In any discussion of oak regeneration and oak regeneration problems, the potential sources of oak regeneration must be considered. By consensus, three categories of oak regeneration are recognized:

(1) Seedlings that germinate and develop following a harvest or disturbance.
(2) Sprouts growing from a stump.
(3) Oak stems of various sizes present at the time of harvest.

The authors tend to discount the first category, seedlings that become established after harvest, as playing an important role in the regeneration of current oak stands. General agreement among authors is reached when the potential sources of future oak regenerations are considered. Seedlings established after disturbances are discounted because they do not compete with faster growing species and/or oak stump sprouts. Stump sprouts are frequently unimportant as a major or primary source of regeneration because large stumps usually do not sprout, and managed stands on medium-to-good sites will contain few small oak trees. Therefore, the consensus is that the regeneration of oak stands in the future is dependent upon developing a population of oak stems that can compete with other species following harvest or other disturbance, and this population will consists primarily of large advance reproduction. In the long term, however, sucessful oak regeneration requires flowering, acorn production, seedling establishment and development, and response to release.

A major purpose of the oak symposium was to provide the best available technical recommendations on how to regenerate oaks. Evaluation of existing oak regeneration potential in the existing stand is essential. Several authors discussed models and methods for evaluation of oak regeneration potential. The authors point out that the development of evaluation models is a complex, time-consuming task. The authors generally agree that, while broad evaluation principles apply, models and methods must be developed to fit local conditions and requirements. Most practitioners can find a method, with some modifications and adaptations, to describe the available sources of regeneration and their expected contribution to the next stand. The practitioner is, in many cases, left with making the decision as to whether existing regeneration potential is adequate or inadequate.

Once a stand or site has been evaluated for regeneration potential, harvest recommendations can be suited to the particular conditions. The authors generally agree that if and when regeneration potential is adequate, the overstory can be removed in one or more cuts. Several authors point out that single-tree selection will not provide for oak regeneration. Thus, the forester who wishes to regenerate oaks will ultimately use a regeneration method that would be classified as even-aged or as group selection.

When a stand or site to be regenerated to oak is judged to have inadequate regeneration potential, several options are available. Harvest could be postponed until the stand evaluation becomes favorable. However, without overt action the regeneration potential may not improve. Therefore, several authors suggest taking steps that will increase the oak regeneration potential. It is suggested that reduction of the understory and intermediate trees under a mature forest canopy will allow the development of existing oak seedlings. While this reduction in low competition will enhance the size of existing oaks, the procedure does not necessarily increase the number of oak seedlings present. It is generally concluded that, as the component of large advance oak reproduction increases, the potential of the stand to regenerate to oaks increases dramatically. Once the potential is judged adequate the overstory should be removed in one or more cuts.

Several papers in the Proceedings deal with the opportunities and problems related to the planting of seedlings and acorns as a means of establishing oak forests. The consensus is that the opportunity and outlook for successful oak planting and seeding is good. While most workers are optimistic about the future of oak planting and seeding, there remain serious words of caution. It is clear that great variation exists in the requirements for planting and seeding success between species, geographic areas, and topographic conditions. It is generally conceded that for the best chance of success the planting and seeding effort must be relatively intense.

Each of the authors emphasizes the particular requirement for an area or species. The following are general observations concerning planting or seeding oaks:

- Carefully match species and site.

- Provide adequate site preparation. Control competition and improve soil condition.

- Use only seedlings that meet known physical and physiological requirements.

- Plant or seed with care. Protect seedlings. Ensure adequate collection, storage, and treatment of seed and seedlings.

- Provide adequate follow-up competition control. Mow, cultivate, or treat with herbicides as needed.

- Anticipate slow early growth and be prepared to provide the treatment needed to keep the seedlings free to grow.

- Consider use of fertilizers, soil amendments, and tree shelters when local conditions are conducive to their use.

Even with careful attention to the above suggestions, planting or direct-seeding remains uncertain. But even with all the uncertainties and the expenses inherent in the procedure, artificial regeneration may offer the best solution to many current and future oak regeneration problems.

The authors of these Proceedings have presented an impressive array of biological and silvicultural information and fused it into practical recommendations. An interested reader must be impressed by the complexity of the subject of oak regeneration and the skill and perserverance that has been needed to reach current levels of understanding. However, the observant reader will quickly perceive that there are many unanswered questions relevant to how oaks regenerated in the past and how best to regenerate them in the future. The following comments will highlight some of the major gaps in current knowledge of oaks:

- How did current stands of oak regenerate?
- What was the role of fire in establishment of existing oak stands?
- Is there a role for prescribed fire in oak regeneration?
- What factors influence oak flowering and fruit maturation?
- Can flower and acorn production be predicted?
- Why do oak seedlings grow so slowly?
- Why are direct seeding and planting efforts succeeding better in the bottomlands than in the uplands?
- Can natural regeneration methods and artificial regeneration methods be combined?
- What are the economic realities related to artificial regeneration of oaks?

Even as the foregoing questions indicate gaps in the knowledge of oak regeneration, it is clear from these Proceedings that much is known about the regeneration requirements of the oak genus. Continual efforts by forest scientists will provide answers to biological questions so that it is likely that oak regeneration in the future will be limited by economic and social constraints.

The objective of these Proceedings was to document trends, problems, and recommendations relevant to oak regeneration. The authors were asked to emphasize proven relationships and to make practical recommendations; they have accomplished their objective and fulfilled their commitment with an excellent aggregation of papers. We, the editors, commend them for their scholarship and thank them for their efforts.

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