The Silviculture of Oaks and Associated Species

a summary of current information
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RICHARD D. LANE, DIRECTOR

FOREWORD

OAKS AND THEIR ASSOCIATED species occupy 48 percent of the commercial forest area east of the Great Plains—more than a third of the total commercial forest land in the United States. These species range from southern New England west to the Great Lakes and beyond, and south to the Gulf of Mexico, supplying most of the hardwood volume used by the Nation's forest-products industries.

Expanding demand for these species throughout their wide range has led to rapidly increasing interest in their management, together with the realization that the knowledge required for such management has been slow to accumulate. In response to this interest, a symposium was presented by the Division of Silviculture of the Society of American Foresters at their annual meeting in Philadelphia, Pa., in October 1968, to summarize present knowledge about the silviculture of the upland oak types and some associated hardwood species. The papers given at this symposium present up-to-date research findings in the fields of natural and artificial regeneration, stand density and growth, site quality determination, and tree improvement.

The importance of the material covered and the demand for copies of the papers made it desirable to provide wider dissemination of this information. I am pleased that the Northeastern Forest Experiment Station was able to play a significant role in both the formulation and publication of this work for the forestry profession.

—R. D. LANE
Director,
Northeastern Forest Experiment Station
Forest Service, U. S. Dep. Agriculture

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MEASURES NECESSARY FOR NATURAL REGENERATION OF OAKS, YELLOW-POPLAR, SWEETGUM, AND BLACK WALNUT

by F. BRYAN CLARK, *assistant director, Timber Management Division, North Central Forest Experiment Station, Forest Service, U. S. Department of Agriculture, St. Paul, Minnesota, maintained in cooperation with the University of Minnesota.*

WE KNOW A LOT about the basic requirements for seed germination and for seedling growth and development of various hardwoods. But to date we have been able to do little to create specific conditions to favor one hardwood species over another. Often good stands follow harvest cuts, but we can take little credit for composition except for yellow-poplar. If we are going to have a real influence on species composition we must be prepared to incur added expense. On most upland oak sites we will have to continue to use extensive means to influence composition. However, such extensive methods as maintaining proper stocking as stands approach maturity appear to do a satisfactory job in relation to the values involved.

The task of the forest manager before harvest time is to find the most economical way to provide environmental conditions that not only favor desired reproduction but also maintain good growth and quality in the maturing stand. To do this, he must know site quality and the silvical requirements of both wanted and unwanted species common to the area.

One of the guiding principles of silvicultural treatments for oaks, yellow-poplar, sweetgum, and black walnut is that these species are intolerant or intermediate in shade tolerance. The stand in which these species grow, whether it covers ¼ acre or 40 acres, must be even-aged.

GENERAL INFORMATION

Little is known about ways to stimulate hardwood seed production. The forest manager must continue to rely on proper stand density and selection to increase seed production. He must develop large-crowned, vigorous trees in the right location to regenerate stands on specific sites. For oaks this means that the desired seed source must be encouraged on the site to be regenerated. Though rodents and birds account for much oak seed dissemination, the seeding range of oak must be considered to be under and adjacent to the seed-tree crowns.

Yellow-poplar is another story. Past research has shown that seedfall patterns are predictable (*6, 11*). We know that most of the seed falls within 300 feet of seed trees. We also know that the seed will be dispersed north and east of a seed tree by the prevailing winds. Thus yellow-poplar reproduction cuttings must be concentrated north, east, and beneath the seed source.

The seedfall characteristics for sweetgum are similar to those of yellow-poplar, and the seeding range is about 200 to 300 feet (*13,15*). Many hardwood direct-seeding trials have failed because rodents and birds pilfered the seed, yet practically all natural walnut seedlings and much oak reproduction originates from rodent-buried seed. For oak and walnut, significant numbers of seedlings are established only during bumper seed years.

The potential for advance reproduction to produce the new stand is receiving more attention. Research now under way promises to yield more definitive information to replace some of the art in silviculture with physiological principles. Yet standards for determining the adequacy of advance reproduction are lacking. Four hundred good stems per acre of desirable species were judged to be sufficient advance understory for making a harvest cut in a poorly stocked stand of upland central hardwoods (*33*). In contrast, for West Virginia oak types, 4,000 advance seedlings per acre were recommended as the minimum to reproduce a new oak stand (*7*). In practice, the type of advance reproduction, whether seedling or seedling sprout, plus species, size, vigor, and distribution, are important considerations—along with total numbers and competition from unwanted trees and shrubs.

Better fire protection, reduced grazing, and lack of fuelwood cutting are proposed by various authors as reasons for increased amounts of unwanted tolerant species in the understories on better hardwood sites. A comparison of burned and unburned areas in Rhode Island showed that fire favored the "intolerant sprouters," white, scarlet, and black oaks (2). The role of fire in favoring certain oak species over other trees relates to the sprouting ability of the oaks. Though many species sprout after the tops are killed by fire, it is vigor and sprouting consistency that give oak the ecological advantage.

Harvest cutting method can influence species composition. However, species vary in their response to how the overstory is removed. In Ohio, cutting intensity had no influence on the total number of oak stems; but after 10 years, clearcut plots had the most oaks in the dominant canopy of the new stand (*26*). For yellow-poplar the story was different: clearcutting with attendant large amount of scarification produced as much as 10 times more seedlings as selection cutting. Most yellow-poplar seedlings established after light cuts die from lack of light and/or moisture. So a number of environmental factors influence the establishment of trees in the new stands. Fortunately, most of these factors can be altered.

OAKS

Oaks are reproduced before the harvest cut, not after. Research in various localities showed that the amount of oak in the new stand depends directly upon advance reproduction[1] (*1,7,22*). The ability of seedlings to become established for a year or two is not the critical factor in regenerating oaks. Flushes of new seedlings in good seed years are characteristic, but most of these seedlings die during the first year or two. It is the ability of some of these seedlings to become well established and grow before the overstory is removed that permits oaks to compete in the new stand.

The build-up of advance oak regeneration on a specific site was found to be related to the particular set of environmental

[1]Sander, Ivan L., and F. Bryan Clark. *Reproduction of upland hardwood forests in the Central States.* In Press, U. S. Dep. Agr. Handbook.

conditions that exist on the site (*7, 8*). In these studies percent of sunlight on the forest floor and aspect were correlated with the amount of advance reproduction. The authors reasoned that on south and west exposures the more open stands permit more sunlight to reach the forest floor and favor oak establishment. They also found that partially cut, lightly burned, or grazed stands had the most advance reproduction.

Amount of established oak reproduction varies greatly. In West Virginia a range of 125 to more than 55,000 oak seedlings per acre was reported (*32*). Moreover, nearly half of the areas studied had at least 3,000 oak seedlings per acre. In other studies the numbers of advance oak seedlings ranged from thousands per acre in Ohio to only 230 per acre in mixed hardwood plots in Indiana.[1]. And plots in southern Illinois had an average stocking of 500 advance and 650 new oak seedlings 4 years after cutting in oak-hickory and mixed hardwood stands.

New sprouts from advance reproduction are the most desirable form of oak reproduction (*26*). Such sprouts develop after established trees are injured during logging or after sudden overstory removal. Six years after cutting in Illinois, new sprouts were 14 feet tall, trees from advance reproduction that did not sprout were 6 feet tall, and new seedlings were only 1 foot tall.[1] Thus the amount, size, and origin of advance oak reproduction strongly influence the composition of the new stand. It is well established that, through fire and other factors causing top dieback, the roots of advance oak reproduction are usually several years older than the tops. It is probably the "imbalance" between top and root size and condition that causes many shrubby, flat-topped oak seedlings to send up a new, vigorous sprout when suddenly released from the overstory. If it were not for this mechanism and logging injury, much advance oak reproduction would compete poorly with other species.

Advance oak reproduction is more abundant on medium and poor sites than on good sites (*23,34*). In New Jersey, oak was easier to establish on well-drained drier sites than on poorly drained sites (*30*). The poorly drained sites had an advance understory of shrubs and herbs that responded quickly to cutting and crowded out oak seedlings. Though such sites produce good hardwood timber, the possibility of economically producing oak stands without special treatment is slim. The lack of aggressiveness in seedling oaks precludes getting enough new reproduction through the rank growth of weeds and shrubs. Though the use of herbicides before harvest holds some promise, the expense of repeat applications for several years cannot be justified for oak. Consequently, we may have to accept mixed hardwoods on good sites and manage for oak where it can be more easily maintained in the dominant stand.

Bottomland species such as pin oak and willow oak are different. Wet-site oaks tolerate flooding that other species cannot survive. However, the weed and shrub problem is acute. As with the upland oaks, advance reproduction is the key to establishing the new stand.

Pin oaks, for example, reproduce in waves, thousands of seedlings per acre following heavy seed crops. The usual dense overstory canopy suppresses the seedlings and they die in dry summer months. Under management, drastic treatments will be necessary to reproduce the common even-aged pin oak stands. The present pure stands are the result of drastic treatment, usually clearcutting and even clearing. Detailed procedures have not been perfected for reproducing pin oak, but research in progress provides guidelines (*24*). Because of the different moisture regimes in uplands and bottomlands, it will not be possible to keep the overstory density in bottomlands as low as on uplands to encourage the establishment of advance reproduction. Keeping the stands too open for a period of 10 to 20 years will encourage the development of a jungle of shrubs and vines. The approach must be to capitalize on the frequent, large seed crops by timing the final cut several years after a bumper crop of seedlings has been established.

Specific data on the influence of light intensity for oak germination and establishment are scarce. Judging from the abundance of seedlings of various oak species that become established under fairly dense stands, high light intensity obviously is not required for germination and early establishment. However, for growth the different oak species probably differ in light requirements. White oak persists as an understory tree much longer than other oaks, but this persistence probably relates to drought tolerance as well as low-light-intensity tolerance. White oak is reportedly more efficient in producing seedlings than red oak (*32*). Recently it was shown that full sunlight produces the most vigorous red oak seedlings (*21*).

The usual 1 or 2 inches of litter had little influence on the number of oak seedlings established through natural seedfall in upland sites (*23*). But in a study of bottomland reproduction, heavy litter restricted hardwood reproduction, including pin oak (*16*). Disking to provide a better seedbed increased the number of new red oaks in Wisconsin (*27*) and pin oaks in Missouri (*24*). However, disking was judged to be economically impractical in both cases. Disking after a bumper seed crop in Indiana greatly increased the number of white oak seedlings. Here again, the number of new seedlings on the undisturbed litter was adequate. With normal litter accumulations there should be no need for disking to increase oak regeneration.

Invasion of mixed oak stands by sugar maple, American elm, American basswood, and other hardwoods has created problems in oak regeneration cuts in Wisconsin (*28*) and elsewhere to the east. These mesic species are evidently invading areas where they had been excluded by wildfire. Lack of advance oak reproduction in southern Wisconsin has caused much concern to forest managers. The stands are about 100 years old and date back to the time when the widespread Indian practice of burning ceased (*10*). Oak brush or "grubs" had survived annual burning, and when the fires stopped, these trees developed into stands that probably represent a fire subclimax. Stand treatment and/or density have prevented the establishment of advance reproduction that can compete successfully with the other trees, shrubs, and weeds when the overstory is removed. Obviously we must find a more efficient way to establish oak reproduction other than by repeated wildfires. We need to know when and how to thin stands to permit the establishment, growth, and development of advance reproduction. Getting new seedlings is only a small part of the problem. New seedlings must be nurtured to the point where they are vigorous enough to compete with other plants when released by harvest cutting.

Why is reproduction lacking in places like Wisconsin, Minnesota, Iowa, and possibly Missouri while seemingly the problem is not so prevalent in states to the east? Fire may be the answer. Forests in the western edge of the oak range are the result of annual Indian-, settler- and farmer-caused fires. Now the fire-born stands have come of age and enough time has not passed or the treatment has not been right for the development of an oak understory. If time since fire cessation is an important difference between eastern and western oak stands, then the forest manager is in for a difficult job in reproducing oak where well-developed advance reproduction is absent. Site quality and stand age are undoubtedly contributing factors. By multiplying the probabilities of (1) an oak seed crop, (2) a season favorable for germination, and (3) conditions favorable for understory seedling growth, it is easy to see that, left to chance, it will take many years to reproduce oak stands where advance reproduction is lacking.

Advance reproduction must be capable of responding vigorously to release after harvest cutting in order to stay dominant. Recently, the response of individual oak seedlings to a heavy, single-tree selection cut was studied in detail (*5*). This study showed that for red and white oak seedlings, crown conformation (whether the seedling is flat-topped or single-stemmed) was the key factor in predicting seedling vigor following release. Variation in sunlight from 6 to 90 percent failed to yield a significant growth correlation. It was concluded that either the shade-tolerant seedlings received adequate light or that the root systems did not completely adjust to the new growing conditions during the 4-year study period. Careful study of individual trees showed that non-erect seedlings tend to straighten; flat-topped seedlings respond gradually and some establish active leaders; and a few flat-topped seedlings produce a basal sprout after release.

Clearcutting a southern Michigan oak stand after a good acorn crop failed to produce a new stand with oak as an important component (*14*). Oak seedlings were established but did not grow fast enough on this good site to compete with more vigorous species. The few oaks established in the new stand are sprouts. This case is not isolated; experimental cuttings on good sites in Indiana gave the same results. In the Michigan studies the authors suggested that early cleanings must follow harvest cuttings on good sites. This prescription might keep advance reproduction in the new stand but probably not newly established seedlings. Mistblowing was unsuccessful in controlling brush to release oak in Wisconsin because of regrowth and lack of herbicide selectivity.[2]

Arend and Scholz[2] recommend a two-cut shelterwood system where oak advance reproduction is lacking. They cite examples where three-cut shelterwoods in Wisconsin resulted in about 3,000 seedlings per acre. They also suggest the possibility of disking and mowing to control brush and encourage oak sprouts.

Because of the prevalence of advance oak reproduction in West Virginia, the one-cut shelterwood method has been suggested for regenerating areas ready for harvest (*32*). A good review of evidence favoring the shelterwood method for oaks is made by Smith (*29*). More recent research corroborates this general observation on the desirability of this method for upland oaks.

The only real difference between this type of shelterwood and one of the common present practices is the current usage of the term *clearcutting*. Smith suggests the use of the term *shelterwood* is best from the silvicultural standpoint if advance reproduction is involved. The so-called one-cut shelterwood differs from clearcutting in one important aspect: shelterwood presupposes adequate reproduction of desirable species before the final cut. If the shelterwood concept is carefully followed, the forest practitioner will avoid one of the pitfalls of even-aged oak management. While lack of advance reproduction does not seem to be a problem on most upland sites in the East, experience in the western edge of the oak range indicates that the inadequacy of advance reproduction must not be overlooked.

The sudden removal of an overstory not previously thinned or partially cut generally results in an even-aged stand originating from tolerant advance reproduction and intolerant new seedlings of such species as yellow-poplar. If the site quality is high enough, this might be the best treatment for obtaining the new stand. If the site is best suited for oak, then the more classical shelterwood approach is probably best. Here the objective is to grow an even-aged stand during the first 30 to 40

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[2]Arend, John L., and Harold F. Scholz. *Oak forests of the Lake States and their management.* U. S. D. A. Forest Serv. Res. Pap. NC-31, 36 pp. N. Cen. Forest Exp. Sta., 1969.

years dense enough to produce quality stems. Then by favoring species and quality, stand density is reduced to about 60 square feet of basal area per acre to permit continued crown development on trees selected for maximum growth and seed production. After this cut there is enough light and moisture to permit oak establishment but not enough to encourage the rapid development of intolerants. A cut that is too heavy at this point may encourage unwanted trees and shrubs. One or two more thinnings upgrades the residual stand quality and provides more overstory growing space. At the same time more oak becomes established and seedlings grow into the sapling stage. Finally, the overstory is removed and the well-developed understory is released to grow into an essentially even-aged stand.

Caution must be practiced in using the shelterwood method to encourage oaks. In a harvest-methods study in southern Indiana uplands, a preparatory shelterwood cut removed about half of the board foot volume. New oak seedlings became established before the final cut, but these new seedlings could not compete with the advance growth stimulated by the heavy cut. Five years after cutting, dominant- and codominant-tree heights in the shelterwood and clearcut plots were as follows:

	Shelterwood (feet)	*Complete clearcut (feet)*
Red oaks	2.0	8.5
White oaks	4.8	11.0
Yellow-poplar	6.6	12.0
Sugar maple	4.5	14.2

The trees left in the shelterwood suppressed growth but did not increase the number of oaks in the dominant stand. Removing the shelterwood residual overstory caused much damage to understory trees.

So the balance between not enough light and moisture and too much is delicate when attempting to establish advance oak reproduction. Long intervals between cuts or repeated light cuts may also encourage the development of dense understories, especially on bottomland sites (*31*). The consequence of understocking on bottomland sites can be costly in understory control or in lengthening the rotation. Much remains to be learned about composition control in bottomland hardwoods.

YELLOW-POPLAR

Though the seed-tree method has been proposed for reproducing yellow-poplar, there appears to be little justification for the method in the light of recent knowledge (*9,4,19*). Yellow-poplar seed remains viable for several years in the forest floor, so successive seed crops accumulate in the litter and germinate when moisture and temperature conditions are right. During a period of at least 2 or 3 weeks before germination, yellow-poplar seed must be continuously moist. This is why a scarified seedbed is best for yellow-poplar. Normally seed in and on litter dries out quickly after rain and cannot germinate. On a scarified seedbed the seed is in contact with mineral soil, which does not dry out as fast as the litter. Some seed is actually covered by mineral soil, and its chance of staying moist during the critical germination period is even better.

Yellow-poplar seed trees are not necessary as insurance against accidental fire or a dry spring. If yellow-poplar seedlings do not develop the first year after cutting, the seedbed deteriorates through the growth of weeds, shrubs, and other tree species. The possibility of second- or third-year establishment is remote. New seedlings do germinate the second and third year after cutting, but they cannot compete with the advance growth.

Scarification from normal logging is ample for preparing yellow-poplar seedbeds. Horse-logging in an Indiana clearcut scarified 17 percent of the area and there were enough yellow-poplar seedlings to stock the entire area although the seed trees were scattered. Undisturbed seedbeds with an excellent seed source produced only 3,000 yellow-poplar seedlings per acre after a heavy cut compared to 30,000 seedlings per acre in the scarified areas (*12*). In this case logging scarified 27 percent of the areas, and 82 percent of the quadrats were stocked. However, scarification in addition to logging may be good insurance in areas with widely scattered seed trees.

With a good seed source, disking or burning was not essential to obtain a good catch of yellow-poplar seedlings in New Jersey and Maryland (*19*). Undisturbed seedbeds had satisfactory stocking on practically all study areas. In this study burning was found to be just as effective as scarification in providing a suitable seedbed. Destruction of the current seed crop by burning was further proof that yellow-poplar seed remains dormant in the duff.

Good stands of yellow-poplar reproduction have followed cuttings made throughout the year. For example, a summer harvest produced 6,000 yellow-poplar seedlings per acre and a winter harvest 10,000 per acre.[1] The area had a good seed source. Spring scarification produced as many seedlings as fall scarification in an Indiana test. However, in a date-of-scarification study during the growing season, June, July, and August treatments produced fewer seedlings than May treatment. Most seed in the summer-scarified plots did not germinate until the following spring, and the new seedlings were too small to compete with the advanced vegetation. So in areas with a poor yellow-poplar seed source, summer logging should be avoided.

The difficulty of controlling honeysuckle in bottomland yellow-poplar sites is typified by experience reported from South Carolina (*3*). Because of past experience with honeysuckle, the harvest area was broadcast-sprayed with herbicide for 2 years after cutting. Top and root kill were good, but vigorous new honeysuckle seedlings developed from seed stored in the litter. Yellow-poplar seedlings were released once a year for 5 years, but over half of the seedlings were dead within 5 years regardless of release. And the competitive position of released seedlings was not improved. Pre-emergence herbicides were suggested as a possible solution to the problem, but such a prescription would only work after the yellow-poplar seedlings are established. A mixture of 2,4-D-picolinic acid is recommended to control honeysuckle before regeneration cuts for yellow-poplar in the Northeast (*20*).

The economic practicality of understory control to encourage yellow-poplar establishment remains to be determined. A single application of ground herbicide to aid establishment would cost $15 to $20 per acre. Because of variable effects, the use of fire for understory control must be carefully evaluated before it is recommended.

Openings at least 1 acre in size are recommended for best yellow-poplar development. Smaller openings are inefficient due to the high percentage of the area shaded by the edges of the adjacent forest canopy (*19*). In central hardwoods, opening size from 1/8 acre to 5 acres did not influence the amount or composition of reproduction 2 years after cutting.[1] However, opening size did influence growth. This same relation has been demonstrated for yellow-poplar in Tennessee.[3]

SWEETGUM

Sweetgum has been compared to yellow-poplar for many silvical requirements but always with the qualification that it is more tolerant of wet sites. For example, sweetgum represented 68 percent of the desirable understory seedlings on wet sites but only 27 percent on moist sites on the New Jersey Coastal Plain (*25*).

Experimental shelterwood cuttings on two small bottomland areas in New Jersey provided fairly good sweetgum stocking in the new stand (*31*). The original stand was composed of red oak, sweetgum, white oak, and red maple. Neither cutting area contained a sweetgum seed source, but abundant seed was supplied by trees adjacent to the plots.

Recent research shows that root sprouts from preexisting buds are important for sweetgum regeneration in the Piedmont of Georgia (*18*). This has been substantiated by a seed-tree cut in a loblolly pine-mixed hardwood stand in coastal South Carolina, where sprouts accounted for much of the sweetgum in the new stand.[4] Twenty to fifty root sprouts were found to be originating from individual parent trees.

Based on results of clearcutting pole-sized sweetgum stands in Mississippi, coppicing has been proposed for regeneration where pulpwood production is the primary goal (*17*). Six years after cutting, 800 to 900 sprouts per acre stocked the cut areas. Growth was rapid and no treatment was necessary after the harvest. It was suggested that many small even-aged patches of sweetgum in hardwood stands originate as sprouts.

Natural seeding cannot be discounted as a means of regenerating sweetgum. The invasion of agricultural land formerly

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[3]Smith, Henry W., Jr. *Establishment of yellow-poplar (Liriodendron tulipifera L.) in canopy openings.* Unpublished Ph.D. dissertation, Yale Univ. School of Forestry, 1963.

[4]Hook, Donald, Paul Kormanik, and Claud Brown. *Early development of sweetgum root sprouts in coastal South Carolina.* Unpublished manuscript, U. S. D. A. Forest Serv. Southeast. Forest Exp. Sta., 1968.

cultivated is ample evidence of the aggressive nature of this species through seeding. But we must take a closer look at new and old cuttings before we establish guidelines for regenerating sweetgum in a variety of situations.

BLACK WALNUT

Squirrels are responsible for practically all black walnut reproduction. Nuts are usually squirrel-planted within 300 feet of the seed source, so careful planning is needed to regenerate this species. Seed sources must be left adjacent to patch clearcuts or group-selection openings. In experimental harvest cuttings in Indiana, few seedlings were produced by the selection system but more than 200 new walnuts per acre made up a part of the new stand in a 5-year-old clearcut. Seed trees were sparse; the seedlings originated from seed on the area at the time of cutting or from squirrel-planted nuts from adjacent uncut timber. Needless to say, where the site is good enough, black walnut should be favored over all other species. However, it will take cleanings and weedings to bring a significant amount of walnut into the new stand.

In a study of small sawtimber-size walnut trees, openings created for crown release were ideal for the establishment of new seedlings. Evidently the right combination of seed source, canopy opening, and squirrel planting in excess of seed retrieved for food is needed to produce walnut seedlings. The odds against these factors combining to yield seedlings that can compete with fast-growing associate species help explain why walnut is only an occasional tree in the dominant stand.

IN CONCLUSION

Much research and practical experience have brought us to a point where we can give fairly good prescriptions for extensively managing oaks, yellow-poplar, and to a lesser extent sweetgum and black walnut. Unfortunately, extensive methods do not produce consistent results. In practice, results of harvest cutting are still erratic, and a system of intensive treatments remains to be defined and verified through controlled research and practical application. Of immediate concern are general areas of seed production and distribution, understory control, stocking, and management systems that integrate silvical requirements with owner objectives. Bottomlands, with their great productive potential, present our most difficult problems in regenerating the stand.

But we do not have to wait for the final word to make significant improvements in composition control. If we take the information we now have and temper it with basic ecological principles, we can begin to expect more than fortuitous juxtaposition. It is time we stopped taking pot luck in hardwood regeneration.

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ARTIFICIAL REGENERATION OF HARDWOODS

by R. L. McELWEE, *associate director, cooperative programs, School of Forest Resources, North Carolina State University, Raleigh, North Carolina.*

BEFORE DELVING into specifics, we need to consider the reasons for and the philosophy behind artificial regeneration. Irrespective of the methods used, most cultural practices employed in forest management, and particularly regeneration practices, are capitalized expenditures, which must be justified on need and future economic returns. Therefore it is imperative to take a look at the *aims* of regeneration.

Basic to sustained-yield forestry is suitable replacement of harvested stands. If maximum usable production is to be attained on any forested area, regeneration must not only be satisfactory in quality but must follow harvest without undue delay. Within the scope of the numerous economic policies, sites, and species used in forestry practice, many regeneration techniques can be employed, and none can be considered as universally suitable. Each stand should be re-established by the most efficient method consistent with the inherent quality of the particular site involved, the biologic capabilities of the species used, and the management goals and economic capabilities of the landowner.

It is deplorable but nonetheless true that regeneration of hardwoods was not even considered until relatively recently. Successful regeneration was, for the most part, a combination of fortuity and competitive tenacity of the species involved. Denuded and eroded areas, forests of cull individuals, stands composed largely of the less desirable species, all bear witness to failures of this combination and the lack of careful consideration and adequate provision of the silvical requirements necessary for obtaining and maintaining satisfactory regeneration. As a result, there are many thousands of acres of hardwoods to be restocked with thrifty regeneration of desired species before their productive potentials can be even partially realized.

NATURAL VS. ARTIFICIAL REGENERATION

As with conifers, hardwood regeneration can be accomplished by either natural or artificial methods. Though artificial regeneration may be more straightforward, it is in many ways more difficult and requires greater skill; it depends upon plant materials normally obtained outside the immediate planting site in the form of seed, nursery-produced seedlings or rooted or unrooted cuttings. Choice of method—natural or artificial—depends largely on biological characteristics of individual species tempered by individual experience, preference, and costs.

If artificial regeneration is to be used, it must be justified on the basis that less costly natural regeneration will not result in satisfactory stocking of desired species in a reasonable time. For certain hardwoods, particularly the lighter-seeded species, such a justification is often difficult. On better sites such as the alluvial floodplains of major and minor streambottoms and with a reasonable amount of assistance, natural regeneration of desirable species is generally so profuse that planting is not needed. Hosner and Minckler (*1960*), Johnson (*1961, 1964*), and others found conclusive evidence of adequate natural regeneration along stream bottoms. Minckler and Jensen (*1959*), Paton (*1946*), and Tryon and Carvell (*1958)* show similar promising results for uplands.

In his discussion of hardwood planting procedures, Johnson (*1966*) cites four justifications for planting hardwoods. They are: (1) to realize the benefits of tree improvement, (2) to modify and control species composition, (3) to alleviate prospective shortages, and (4) to prepare for future possible intensification of hardwood silviculture. A fifth justification that might well be included is to establish commercial hardwood stands on sites readily accessible for year-round logging.

ROLE OF ARTIFICIAL REGENERATION

Notwithstanding the present limited use of artificial regeneration of hardwoods, there are many situations and conditions that warrant its consideration. Consider, for example, stands that have been subjected to decades of high-grading, and that have few or no satisfactory seed sources. This fairly common condition requires deliberate and forceful methods if the sites are to approach their potential productiveness. Similar drastic measures are required wherever it is necessary to convert to a more desirable species mixture. In many instances an initial planting to obtain the desired species composition may be the only artificial regeneration required; and natural reproduction can provide the stands of succeeding rotations.

Tree improvement, a proven means of upgrading stand and tree quality, has limited potentials with natural regeneration. If genetic improvement is to be applied to hardwoods, artificial regeneration systems are dictated. Dependent upon species characteristics and demands, improved genetic stock must be established artificially by cuttings as in cottonwoods, by seed and grafted stock as in black walnut, or as nursery-produced seedlings. The degree of genetic variation, hazards of inbreeding, and ease of natural regeneration will determine the necessity of artificially regenerating succeeding stands.

Occasionally instances arise where it is desirable to convert from one species or species mixture to another having more economic potential. As an example, let me cite one of our recently initiated studies. Potential shortages of hardwood pulpwood can conceivably be alleviated by extending hardwoods to sites where they normally do not occur. By selecting and propagating appropriate individuals, a strain with commercial potential for nonhardwood sites will be developed. Our work here involves tests of sycamore on sites drier than those on which the species normally develops at adequate rates. Pulpwood rotations will be relatively brief, possibly 10 to 15 years. Though subsequent stands might be initiated by coppice, we feel that periodic planting will be necessary to keep the species dominant. The end result of this program will be successful conversion of sites presently supporting mixed hardwoods or even some of the best pine to stands of sycamore to supply the increased demand for hardwoods.

Because of the fundamentally different reproductive habits among species of hardwood and between the hardwoods and conifers, I believe artificial regeneration of hardwoods will never become as extensive as it has with conifers. There will be continuing need for considerable artificial hardwood regeneration, however, making it necessary that techniques be developed and improved. We must, then, ask the question: "What do we now know concerning artificial regeneration of hardwoods?"

RECOMMENDATIONS

General

Of utmost importance in the successful use of artificial regeneration is the matching of species and suitable sites. Species-site interactions are being vigorously investigated for many valuable hardwoods, so our knowledge is constantly increasing. We know, in general, that of the four genera being discussed, yellow-poplar and black walnut are the most demanding in their site requirements, while sweetgum and certain oaks tolerate a wide range of site conditions well enough to provide satisfactory growth. Yellow-poplar usually grows best on fairly well-drained second bottoms and in mountain coves with uneroded deep soils, although in some sections good growth of yellow-poplar occurs on slopes up to ridgetops. Black walnut also has its best growth on deep, fairly well-drained soils of bottomlands, upland coves, and lower slopes (*Carmean 1966*). Best sweetgum growth is found on alluvial floodplains, but sweetgum can have satisfactory growth on somewhat poorer soils. Oak species vary greatly in habitat requirements: some of the best oaks, such as cherrybark, grow on fairly well-drained bottomland sites, while others such as chestnut oak are adapted to poor sites.

Nutrient amendments through fertilization offer real possibilities for increasing hardwood growth, but before such practices can become standard, biologic and economic potentials must be better understood. Forest fertilization of conifers has proven beneficial to growth and economically feasible in several countries, and the potential benefit of fertilization for hardwoods seems frequently to surpass that for conifers.

Control of competition is necessary for the success of artificial regeneration, as it often is for natural reproduction. On some sites this may be achieved by elimination of cull trees through girdling or herbicide injection; but often mechanical site preparation such as blading, chopping, disking, and bedding—singly or in combination—is needed. On extremely wet sites water control can be beneficial if not mandatory for success.

Selection of the proper establishment technique is, of course, highly important. In general, the light-seeded species are most successfully established by planting seedlings or cuttings, while direct seeding is usually selected as the technique for heavy-seeded species.

Off-site planting and faulty planting techniques have been partially responsible for the failure or poor performance of many plantations, but poor seedling vigor may often be the basic reason. Many nurserymen have grown hardwood seedlings at densities similar to those for conifers: 25 to 30 per square foot. Recent trials show that a density of 7 to 12 per square foot produces the type of vigorous hardwood seedling that is most likely to survive and grow in height the first year after planting. For most hardwood species, best performance is usually obtained from seedlings that have root-collar diameters greater than 0.375 inch. Planting success may also be affected by nursery pruning of root or top, planting depth, and erectness of the seedlings; and these factors are being investigated.

In nursery production of all hardwoods, the beds should be pretreated by fumigation for weed control. Although expensive, it costs far less than hand weeding alone. Even with pretreatment, some hand weeding is necessary.

By Species

The methods described below are currently thought to be the best for individual species, although modifications may be needed to satisfy local conditions.

Sweetgum.—Fruits can be collected readily from felled trees or by climbing or shaking standing trees. Air-drying the fruits releases the seeds along with numerous aborted ovules, which can be removed by screening. The seed can be stored dry at temperatures just above freezing, and then treated to 30-day stratification prior to sowing in nursery beds at densities that produce 15 per square foot.[1] Alternatively, seed can be stored at temperatures below freezing, and stratification can be eliminated.

Outplanting on moist sites should closely follow lifting from the nursery bed; and if storage is necessary, the seedlings must be kept cool and moist. The 1-0 seedlings can be refrigerated at temperatures between 35° and 40° F.

Full sunlight must be provided for established seedlings. Competition from grass can seriously affect growth during the first year and, like overhead shade from competing woody vegetation, can cause the failure of the plantation. Spacing will depend on the product to be grown, but we recommend spacings of 8 x 8 feet to 10 x 10 feet for pulpwood, and closer spacing down to 6 x 8 feet for sawtimber and veneer rotations.

Direct seeding on prepared sites is feasible in areas having plentiful moisture so that seed does not dry out (*McKnight 1965*). Although little experience is available, it is recommended that fall-sown seed not be stratified, though stratified seed should be used in the spring. Techniques of direct seeding are not sufficiently advanced to recommend this practice for extensive commercial use.

Yellow-poplar.–Seed cones are collected in early fall; after air-drying they are broken up by hand or mechanical means, and the individual carpels are removed from the cone axis. The seeds are stored in dry refrigeration or in moving water. If dry storage is used, a 60-day stratification should preceed spring sowing in the nursery. There are also recommendations for fall sowing of yellow-poplar seed in nurseries. Seed germination may be very low, often less than 10 percent, in part because of the large amount of inbreeding forced by the habits of honeybees effecting pollination.[2] Because of the low germination, seed is often sown so it completely covers the nursery bed to a depth of ½ inch. Germination tests will help in judging

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[1]Webb, Charles D. *A study of the effects of seedbed density on nursery stock quality of sweetgum (Liquidambar styraciflua L.) among open-pollinated progenies.* Unpublished report, U. S. D. A. Forest Serv. SE. Forest Exp. Sta., 1964.

[2]Taft, Kingsley Arter, Jr. *The effect of controlled pollination and honeybees on seed quality of yellow-poplar (Liriodendron tulipifera L.) as assessed by x-ray photography.* Unpublished M.S. thesis, N. C. State Univ. School Forestry, 1962.

the desirable thickness of sowing. If germination is better than expected, hand thinning should be used to reduce seedling density to 15 per square foot.

Outplanting on well-prepared suitable sites should be at spacings that provide 60 to 90 square feet of area per seedling. Direct seeding of yellow-poplar has not been sufficiently successful to recommend it for general use.

Oak.—Artificial regeneration of oak is beset with problems at every step. Seed collection is difficult: the most satisfactory way to obtain seed is from felled trees or by shaking. I know of no absolute means of telling when seed is sufficiently mature to collect, although the yellowish-orange color of the endosperm seems to be the best gage for many species. The use of tree shakers offers real possibilities for gathering acorns, but the timing must be carefully judged. Seed collected from the ground after natural seedfall contains a high percentage of weevil-damaged acorns, especially among those falling first. Visual detection of damaged acorns is costly, but is preferable to flotation tests.

Acorns are stored in refrigeration at high humidities, but often germinate in storage. Care must be taken not to damage the radicle when planting. Nursery seeding can be made in drilled rows, with seeds covered by ¼ to ½ inch of soil and mulched with pine needles; or the seeds can be broadcast before rolling and mulching the seedbed. Seedling densities should be held to 10 or less per square foot.

For outplanting, seedlings should be husky, with large diameters and stems 12 to 15 inches long. Seedlings of this size plant well by hand or machine. Removal of all vegetation from the planting site to assure full sunlight is necessary for best establishment of oaks. However, there has been relatively little experience in planting oaks.

More effort has gone into development of direct-seeding techniques, but with varying success. Destruction of seed by rodents has been the chief cause of failure in direct seeding. Use of repellents, screens, or other protective measures has proven necessary in some instances and not in others, depending upon the size and tenacity of the rodent population. In considering the status of our ability to artificially regenerate oaks, I can only conclude that we have much to learn before we can confidently undertake such regeneration on a commercial scale.

Black walnut.—Of the four genera, walnut is the only one for which I believe artificial regeneration is the most productive method of establishment. The potential high value, cultural requirements, and relative scarcity of black walnut in natural stands justify higher regeneration costs than for other species.

Walnut seed is fall-sown to produce densities of 10 to 15 seedlings per square foot. Nuts are covered with an inch of soil and mulched. Seedling quality standards have been devised; they include minimums for both stem caliper and height. As with all hardwood seedlings, care must be taken to avoid the drying of roots.

Outplanting should be on well-prepared suitable sites where control of herbaceous as well as woody vegetation is practiced. Extreme care should be taken in planting; auger holes should be used on some sites. Spacings vary according to site, but I have found no recommendations for planting closer than 8 x 8 feet in pure stands, and some recommendations call for very wide spacings. Walnut is also planted in mixtures with other hardwoods, particularly oak and ash. For development of quality trees, intensive culture in pruning and release should be started at an early age. Some plantations may be made with grafted stock at very wide spacings, and may be managed as a horticultural rather than a forestry enterprise.

As with the oaks, direct-seeding success depends upon rodent control. Fall sowing of unstratified nuts or spring sowing after stratification is recommended, with nuts being placed 2 to 4 inches deep at spacings ranging from 8 x 8 to 14 x 14 feet. Sites must be well prepared, and cultivation equipment must be available. However, until the development of effective rodent-control practices, little consistent success seems possible from direct seeding.

For Maximum Gain

The importance of seed source and seed-tree selection have not been mentioned, but both proper seed source and the selection of superior individuals are mandatory if we are to realize maximum gains through artificial regeneration. Artificial regeneration of hardwoods is an expensive undertaking, because site preparation and seedling costs are high. We need to strive for maximum yields in gross production, quality, or both if artificial regeneration of hardwoods is to be economically justified.

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EFFECTS OF DENSITY, THINNING, AND SPECIES COMPOSITION ON THE GROWTH AND YIELD OF EASTERN HARDWOODS

by SAMUEL F. GINGRICH, *project leader in mensuration research, Northeastern Forest Experiment Station, Forest Service, U. S. Department of Agriculture, Columbus, Ohio.*

THIS IS A SUMMARY of present knowledge about the effect of density, thinning, and composition on the growth and yield of eastern hardwood forests—with particular emphasis on recent literature based on research.

The eastern hardwoods include the upland oaks type; and the bottomland hardwoods type, in which several oaks predominate and where such overstory trees as yellow-poplar (*Liriodendron tulipifera* L.), sweetgum (*Liquidambar styraciflua* L.), and black walnut (*Juglans nigra* L.) are the desired species. These types cover more than 200,000,000 acres of commercial forest land in an area that extends from southern New England to the southern Lake States to Georgia and the Gulf States.

STAND DENSITY IN HARDWOODS

Most hardwood stands, whether even-aged or uneven-aged, develop naturally at high density. In the absence of thinnings or catastrophic events, the growth rate of individual trees is slow, and the stand mortality is high. While much has been said about the understocking of hardwood stands, this general condemnation of understocking usually refers to an understocking of high-quality trees or desired species and not to stocking per se.

One has only to compare the stand development of natural stands (as projected in yield tables) with the results of thinning experiments to obtain some idea about the effects of stand density on tree growth. Many of the desirable intolerant species such as black walnut, yellow-poplar, and the ashes (*Fraxinus* sp. L.), unless able to maintain a dominant crown position, succumb to natural mortality. The highly competitive growing conditions in dense stands produce low-vigor trees that grow far below their potential rates. Overstocking in hardwoods may be more damaging than understocking.

There are other conditions of hardwood density where different problems prevail. Many hardwood stands have been high-graded, burned, grazed, and generally mismanaged for decades. Repeated harvesting of high-quality hardwoods has caused stand quality to deteriorate. A cull volume ranging from 40 to 60 percent (9) is common in many areas. Low densities under these conditions compound the problem, and the desired silvicultural practices range from some type of removal cut to a policy of wait-and-see.

THINNING HARDWOODS

Ask any forester what constitutes a managed forest and his answer will probably include thinning. Thinning is described in most textbooks as a necessary forest-management activity. Much has been written about the subject. However, of the published information that tells how thinning affects growth of hardwoods, little is based on experimental results. And almost nothing has been published about the economics of thinning.

For the sake of this discussion, thinnings will be considered as the removal of trees in immature stands where reproduction is not an immediate objective. There are generally two different philosophies about thinning: thin for future benefit, or thin for present gain. The first emphasizes improvement of the residual stand; it may be a precommercial thinning or a commercial thinning. The quality, vigor, and spacing of the trees in the residual stand are given primary consideration. The second emphasizes the economic feasibility of the thinning operation; the condition of the residual stand is of only secondary importance.

Biologically, and perhaps economically, the two philosophies seem to conflict. That is one reason why it is difficult to generalize about thinning. However, opinions about thinning do not always mean disagreement about basic principles. Often they represent the varying circumstances of a situation.

What is the present state of knowledge about thinning hardwoods? First, consider precommercial thinnings. There is broad support in favor of precommercial thinnings of hardwood stands among silviculturists (*2, 11, 13, 15*). Young, vigorous hardwood stands with desirable species composition on better-than-average sites would appear as ideal conditions for precommercial thinnings. During the first quarter of a rotation there is good opportunity to alter species composition and select quality stems. This is also the time to improve tree spacing and to maintain crown vigor.

The case against early thinning generally rests on the effect of lower densities on stem quality, particularly the development of epicormic branches from suppressed buds on merchantable stems. This presents a dilemma to the silviculturist whose objective is to grow high-quality timber.[1]

On the one hand he is forced to grow large timber fast, risking a reduction in quality; and on the other hand he is keenly aware of the price differential between high- and low-quality timber. And in some cases the only justification for thinning is higher quality yields. Thinning hardwoods may not be a matter of volume production only but a compromise between high-volume production and high financial return.

First thinnings in high-density hardwood stands do not always produce the expected growth response. Because such stands contain low-vigor trees, dense clumps, and mixed species, the first thinning may actually result in a net growth deficit. Holcomb and Bickford (*6*) suggested that spacing, soundness, and vigor of residual trees may be more important than relative growth in the first cutting or two. Haney (*5*) reported that unthinned white oak clumps (*Quercus alba* L.) on poor sites in the Virginia Piedmont produced 108 percent more merchantable volume than clumps that were thinned to a single remaining stem. Tepper and Bamford (*19*) found that low thinnings in oak-sweetgum stands on poorly drained sites in New Jersey did not increase the 10-year growth of either the

[1]Normal yield tables for upland oak (*17*) show that on site index 70 only 8 percent of the trees reach the minimum size required for No. 1 hardwood sawlogs in 100 years.

entire stand or of selected crop trees. Trimble and Tryon (*22*) found that crown encroachment into openings cut in 40- to 55-year-old Appalachian hardwood stands was surprisingly slow for red oak (*Quercus rubra* L.) and yellow-poplar. To obtain maximum benefits from thinning, Roach and Gingrich (*16*) suggested that first thinnings should be made before the stand is 60 to 70 years old on medium sites.

Substantial growth responses from thinning have been reported in the South and on better than average sites in the North. Putnam *et al.* (*13*) reported that diameter growth of individual trees on average bottomland sites might be increased by 30 percent under intensive management and close to 40 percent if the sites were occupied by entire stands of the more desirable species. Apparently results from thinning hardwoods depend more on *species composition, tree vigor,* and *potential stem quality* than merely the growth responses due to reduction of stand density.

Species Composition

The intimate mixture of species in most hardwood stands is a complicating factor in growth studies. Most foresters have favored one species over another on the basis of commercial value or management goals. Very little is known about the biological performance of various species mixtures in the thinned stands.

The number of possible species mixtures is so large that it is impractical to study the effects of species composition in much depth by using permanent replicated plots. But the relative diameter growth rates of hardwoods are generally known.

The differences are so great among associated species that a thinning schedule aimed at increasing the number of fast-growing species would appear to produce a substantial yield bonus over a schedule where species composition is ignored. Putnam *et al.* (*13*) report 10-year diameter growth rates for 11 southern hardwoods ranging from less than 2 inches to more than 6 inches under similar stand conditions. McIntyre (*12*), Trimble (*20*), and Gingrich (*4*) have published growth rates for the principal oak species. Their studies show that trees in the red oak group will grow much faster than trees in the white oak group under the same density and site conditions.

Tree Vigor

The lack of conclusive results in hardwood thinning studies is often due to a lack of knowledge about residual tree vigor. Too often the forester has assumed he could perform growth miracles by the thinning process alone, while giving little attention to the growth capabilities of the trees released by the thinning. Oaks, in particular, can survive many years under high density conditions at growth rates as low as 15 rings per inch. Many such oaks do not have the crown or root systems to respond to the thinning release.

It is becoming more evident that many hardwoods that have endured long periods of high competition are not good candidates for thinning. Weitzman and Trimble (*24*) developed four vigor classes for northern red oak and chestnut oak (*Quercus prinus* L.) based on several crown characteristics. Their studies showed that, for a given diameter class and site quality, a high-vigor tree will produce five to six times more volume growth than a low-vigor tree. Holcomb and Bickford (*6*) found similar results with yellow-poplar vigor classes. Walters (*23*) found that the best indicators of the growth potential of oak and yellow-poplar seedlings are their immediate past growth and present crown position. Carmean and Boyce[2] found that the fastest growing dominant trees in upland oak forests maintain a live crown length that is about two-thirds of total tree height.

Potential Stem Quality

Another important factor in thinning hardwoods is the potential stem quality. Like vigor, a system of classifying stem quality will provide valuable guidelines for marking. The grade of hardwood logs and trees depends on the clear space between defects rather than on the size of defects.

Therefore one of the major goals of stand manipulation for quality production should be to develop a moderate number of stems per acre that have a good proportion of clear bole (*25*). Ward (*26*) presented a strong case for maintaining high-density stands that will favor natural pruning. He found that approximately 50 percent of the variation in clear-volume index of

[2]Carmean, Willard H., and Stephen G. Boyce. *Quality of site affects the quality of oak logs.* In press. U. S. D. A. Forest Serv. North Central Forest Exp. Sta.

individual red oak trees was directly proportional to the degree of crown competition or stand density around the sample tree. Carmean and Boyce[2] also recommended high initial stand densities in very young upland oaks stands to avoid excessive growth of knotty annual rings.

Farther south, Kormanik and Brown (*8*) have done considerable research on some of the physiological aspects of epicormic branching in sweetgum and yellow-poplar. They believe that associated with the phyllotaxy of the tree there is a physiological control that governs the eruption of suppressed buds. They anticipate methods of controlling epicormic branching in some of the southern hardwoods. Weitzman and Trimble (*24*) indicated that some species clear up faster than others under identical conditions of age and size, suggesting that species appear to have a built-in grade potential just as they have a built-in growth potential. Holsoe (*7*) found that difference in the clear-bole length between thinned and unthinned 20-year-old white ash stands disappeared by age 40.

Most research confirms Smith's (*18*) philosophy that dominant trees with full vigorous crowns are less likely to develop new branches after exposure than those that have unthrifty crowns or are from lower crown classes. The best way to avoid epicormic branching is to develop good crowns by thinning and to maintain crop trees as dominants throughout their lives. Boyce (*2*) offered one solution to the problems of epicormic branching and quality. He recommended butt-log silviculture on good sites where the emphasis is on fast growth of a few well-spaced superior trees that will develop large crowns.

It is apparent that for thinnings to be more effective, a system of tree classes that incorporates species response, vigor, and quality potential is necessary. Investments in cultural practices could be made with greater assurance of improving timber quality. Boyce and Carpenter (*3*) have published provisional grade specifications for hardwood growing-stock trees (d.b.h. 7 to 15 inches). They developed a technique based on a simple count of surface-indicator defects on the butt log with allowance for crown class and scaling deduction–a technique that is useful in determining the probability of a given tree producing a certain grade of sawlog. Too often the assumption has been made that the mere removal of rotten or defective trees will increase the number of grade 1 logs produced by a stand. However, it is more efficient to concentrate cultural efforts and costs on selected trees rather than on whole stands in the hope of improving the quality of the residual trees.

YIELDS

Yield information based on long-term studies of managed hardwood stands is scarce. Normal yield tables are availabe for upland oak (*17*) and yellow-poplar (*10*). But the limitations of normal yield tables are well known. Baker (*1*) gave an example of the erroneous reasoning about yield from thinning. He said: "On the one hand, foresters have computed growth of stands by comparison with yield tables by direct proportion; reasoning that if stand A has 80 percent of normal basal area, its growth is 80 percent of the yield table value. And on the other hand, in all seriousness, they recommend thinnings to remove perhaps 20 percent of the basal area to increase growth. Obviously something is seriously at fault."

An attitude prevails today among silviculturists–encouraged to some extent by economists–that the science of forestry will be enhanced considerably when yield tables or equations for managed stands become available. However, several factors should be recognized.

First, the oldest growth studies in the hardwood types discussed here are no more than 20 years old–only a fraction of the anticipated rotations. Second, the problem of quantifying yields for various management schedules is compounded by the kinds of information that could be generated from any particular hardwood type. Realistically, it is impossible to expect anyone to publish in one neat package yields in numerous units of measurement for all combinations of thinning schedules, species mix, management goals, by site quality, utilization standards, and so on. I submit that even if we had all-purpose yield information based on rotation-length studies, our planning horizons would still be limited to 10 to 20 years.

Some yield estimates are available for rather localized timber conditions, and considerable research effort in this is under way throughout the hardwood region. Roach (*14*) estimates that rotations for upland oak in the Midwest can be reduced by 40 percent where thinning is begun early in the life of the stand. Trimble and Mendel (*21*) have synthesized yield data for northern red, white, and chestnut oaks. They have developed rates of value increase and financial maturity tables by site index and tree vigor classes for both volume growth and quality changes.

The need for more hardwood growth and yield research has been promoted by several trade journals, numerous hardwood associations, and industries. Many universities have embarked on basic investigations of hardwood growth research. The U. S. Forest Service has a research program for hardwood stand-density studies. All this gives some promise of more and better yield information soon.

DISCUSSION

In analyzing the current information about growth and yield of the eastern hardwoods, we can see great promise in some of the research being done. However, we still need a better understanding of the basic principles of tree growth, particularly growing space, tree vigor, and potential stem quality.

Though the regulation of stand density offers good opportunity to increase yields, other factors must be considered. The difference in growth between a low- and high-vigor tree might be considerable greater than the difference in growth due to density alone. Differences in growth due to site quality may also be greater than those due to stand density alone. Rates of return are several times higher when quality increases are considered than when only volume growth is considered.

The magnitude of these differences is extremely high among hardwoods, and these factors need to be given more consideration when thinning hardwoods. One of the most important attributes of a hardwood silviculturist is his ability to recognize quality or potential quality of the young tree.

Finally, the most useful information from growth studies would be stand tables resulting from different types of thinning schedules. These tables will provide the basic information for any potential customer to make the necessary conversions to whatever unit he may want.

There are some crucial voids in our knowledge of stand density, thinning, and species composition as they relate to the growth and yield of hardwoods. Some of these voids have been recognized and are under study. Mensurationists are beginning to gain more insight into the components of stand growth through the study of individual trees, and biometricians have had some success in developing nonlinear growth models for mixed stands. Silviculturists, mensurationists, and economists are realizing more and more the need to utilize current growth information, incomplete and imperfect as it may seem, in the resource decisions that must be made now.

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SITE QUALITY FOR EASTERN HARDWOODS

by WILLARD H. CARMEAN, *project leader in site requirements for northern hardwood forest species, North Central Forest Experiment Station, Forest Service, U. S. Department of Agriculture, St. Paul, Minnesota.*

QUANTITY OF YIELD for hardwoods, as for conifers, is greatly influenced by site quality. Quality of yield also varies greatly with site quality. On good sites large volumes of high-grade hardwoods can be grown in relatively short rotations; in contrast, poor sites produce only small amounts of low-grade hardwood products and rotations are long. Accordingly, good hardwood management requires that site quality be carefully identified so that each parcel of land may be managed to grow the hardwood species and products it is best adapted to producing. Furthermore, knowledge of hardwood site quality is necessary so that heavy investments are restricted to excellent sites capable of producing large volumes of high-grade timber–prime hardwood timber that can command high prices for valued products such as furniture and veneer.

Unfortunately, we have only meager information about the site requirements for the many species of valuable eastern hardwoods. We have only limited knowledge about yields of hardwood species at different levels of site quality, or at different intensities of silviculture. However, we do have considerable information about site quality for many of our eastern hardwoods. This scattered information gives us a general picture of the variation in site among various hardwoods and, further, about the soil and topographic features often related to site changes for hardwoods.

DIRECT MEASUREMENT

The most widely accepted method for evaluating site quality in the United States is the direct estimation of site index. Height and age measurements from dominant and codominant trees are used with published site-index curves to estimate how tall trees will be at an index age—usually 50 years for eastern hardwoods. Site index is then related to yield tables to estimate growth and yield of forest stands at various stand ages. A total of 26 different site-index curves have been published for 16 eastern hardwood species (table 1), and many of these curves have been reproduced in a summary publication (*32*).

The site-index method is simple and easy to apply when suitable forest trees are available for the required height and age measurements. However, in many hardwood forest areas suitable trees are lacking because stands may be uneven-aged, poorly stocked, too young, damaged by fire or heavy grazing, or may have been subjected to various intensities of past cutting. Satisfactory site-index measurements can be taken only from dominant and codominat forest-grown trees that have been free-growing and uninjured throughout their lives. Such trees most commonly occur in even-aged fully stocked hardwood stands that have not been disturbed by past cutting. For example, in the Central States many even-aged upland oak stands occur in areas formerly clearcut for charcoal. Dominant trees in such even-aged oak stands are very well suited for site-index measurements, just as are dominant trees in even-aged conifer stands.

Most trained foresters should know how to select proper trees and stands for site-index measurements. But errors in site-index estimation still may occur even when suitable forest trees are available for measurement. These errors occur when regional harmonized site-index curves do not accurately portray the variable patterns of tree height growth that are found within many large forest regions (*17*).

Many of our important hardwoods, such as upland oaks and yellow-poplar, occur over extremely wide geographical areas. Within these large areas there are great differences in soil, topography, and climate; and these differences may cause great variation in site quality. However, in addition to site-quality variation, these differences may also be associated with variable

Table 1.—Site-index curves for eastern hardwood forest species

Tree species	Area	Reference
Upland oaks	Eastern States	Schnur (*58*)
	Piedmont & South Appalachians	Olson (*50*)
Red oak	Lake States	Gevorkiantz (*29*)
Hickory	Central States & Appalachians	Boison & Newlin (*7*)
Yellow-poplar	Central States & Appalachians	McCarthy (*45*)
	Piedmont & South Appalachians	Beck (*6*)
Sugar maple	Vermont	Curtis & Post (*19*)
	Vermont	Farrington & Howard (*26*)
	Vermont	Hawes & Chandler (*36*)
	New York	Farnsworth & Leaf (*25*)
Red Maple	Connecticut & Massachusetts	Foster (*27*)
Yellow birch	Vermont	Curtis & Post (*19*)
White ash	Vermont	Farrington & Howard (*26*)
		Curtis & Post (*19*)
Black walnut	Central States	Kellogg (*41*)
Black locust	Central States	Kellogg (*42*)
	Long Island	Hopp & Grober (*39*)
Sweetgum	Maryland	Trenk (*62*)
	Southern alluvial soils	Winters & Osborne (*68*)
	Mississippi Valley	Broadfoot & Krinard (*12*)
Cottonwood	Mississippi Valley	Broadfoot (*8*)
	Central States	Neebe & Boyce (*48*)
Cherrybark oak	Mississippi Valley	Broadfoot (*9*)
Water oak	Mississippi Valley	Broadfoot (*10*)
Swamp blackgum and tupelogum	Southeastern Georgia	Applequist (*1*)

patterns of tree-height growth. Trees may follow entirely different patterns of height growth in order to arrive at the same height at 50 years—that is, the same site index. Accordingly, the height-growth pattern portrayed in a single set of regional site-index curves may not accurately represent the diverse height-growth patterns actually found in widespread geographical areas.

Considerable evidence is available to confirm that variable height-growth patterns exist on different sites, soils, or in different portions of large forest regions (*17*). This evidence includes:

- Contrasting harmonized site-index curves where two or more sets of curves are developed for different portions of the range of a particular species: for example, the three sets of site curves for upland oaks listed in table 1 show definite contrasts in patterns of tree-height growth.

- Periodic height-growth measurements from permanent study plots that show height growth different from the growth predicted by harmonized site-index curves.

- Soil-site studies that indicate variable height-growth patterns on contrasting soil or topographic conditions.

- Stem-analysis studies that reveal actual height growth for trees growing in areas of contrasting site quality. These stem analyses frequently reveal polymorphic height-growth patterns decidedly different from the patterns portrayed by conventional harmonized site-index curves.

Errors in site estimation due to faulty site curves may be particularly large for very old or very young forest stands. Of course, no error occurs when trees are 50 years old because their present height also is site index. But site-curve errors become progressively greater with increased number of years from the index age of 50. Accordingly, when we are uncertain about the applicability of regionwide site curves we should measure trees as close as possible to 50 years. Trees ranging from 35 to 65 years are usually acceptable.

Variable patterns of tree-height growth mean that we must carefully evaluate the applicability of all regionwide harmonized site-index curves. In many cases we may find that a single set of site curves cannot adequately express the different growth patterns for tree species that have wide geographical ranges, or that have wide ranges of site quality. Thus several sets of local site-index curves may be needed to describe more accurately the pattern of tree-height growth produced by local soil, topographic, and climatic conditons. Polymorphic site-index curves based upon stem-analysis techniques are recommended.

Species Comparisons

Many stands suitable for site measurements may not contain the tree species for which site-index estimates are desired. Dominant trees of several species may be present, but no usable trees of the particularly desired tree species may occur. For such stands we can estimate site index by using the tree species that are actually present. Then species-comparison graphs can be used to convert site index of the measured trees to site index of other desired tree species. Species-comparison graphs have been published for hardwoods in the southern Appalachians (*23*), for the Piedmont (*49,51*), for Vermont (*20*), and for white pine and red maple in Connecticut and Massachusetts (*27*). Site-index ratios among various species of oak have been listed by Trimble and Weitzman (*64*).

Species comparisons are a very useful means for extending the application of direct site-index estimations. Additional comparison studies are needed covering additional tree species and forest areas. These comparisons are particularly helpful in judging which species is most productive on particular sites. However, we should bear in mind that the comparisons are based on tree-height growth alone. Therefore we should also base the choice of species on additional comparisons, especially of volume and value of yield, where possible.

INDIRECT METHODS

Measurements of site index from standing trees are very satisfactory whenever suitable trees occur, and when we have suitable site-index and species-comparison graphs. But the land may be devoid of trees, or trees may have been injured by fire or heavy grazing, stands may be too young or may be uneven-aged, or indiscriminate cutting may have removed the free-growing dominant and codominant trees needed for direct site-index measurements. Therefore methods of site evaluation are needed that are applicable to all forest land regardless of the composition or condition of existing cover.

Three indirect methods of estimating site index have been developed.

Understory Vegetation

Plant indicators of forest site quality are widely used in northern Europe and Canada. However, the method has received relatively little attention in the United States. Understory plant communities are relatively simple in northern coniferous forests, and only two or three species are usually dominant in the understory on sites of a particular quality. In contrast, hardwood forests in more southerly latitudes have a much greater number of understory species. These species may occur in a great variety of combinations; and many of them occur over a broad range of site quality. In addition, the plant-indicator method may be difficult to apply in recently disturbed forests or in forests having great contrasts in composition and stocking. And this method cannot be used during dormant seasons if it is based on herbaceous plants.

Despite these limitations there are certain understory species that occur on a rather narrow range of site quality—that is, species that have narrow ecological amplitudes. And these relationships could undoubtedly be better defined if quantitative ecological techniques are used. But because of complexities in composition, it is unlikely that site quality for eastern hardwoods can ever be defined on the basis of only a few understory plant species. Instead, on each site we would probably have to rely on a spectrum of several species of key plants, each of which will require an evaluation for abundance (*38*).

The plant-indicator method can be a useful supplement to other site-evaluation methods. Understory vegetation may be particularly useful in mapping forest soils and site quality because understory vegetal changes frequently indicate boundaries between soil and site-quality classes.

Soil Surveys

Soil surveys for agricultural lands in the United States have been made for more than 60 years. At first, attention was given only to productive agricultural lands. Rough broken land, suitable only for tree growth was either ignored or received only superficial attention. But in recent years increased attention has been given to forest lands, and in most states modern soil maps are being prepared for all lands, both agricultural and forest. The U.S.D.A. Forest Service has active soil-inventory programs under way for National Forest lands, using methods similar to those of the National Cooperative Soil Survey (*57*).

Most recent forest-soil surveys contain tables that give interpretations of site quality for forest growth, as well as for other features including competition, regeneration potential, trafficability, disease hazards, etc. (*43,57*). Some of these interpretations are based on quantitative data gathered in the course of the soil survey. However, in many cases interpretations are based on limited data or on the subjective opinions of soil scientists and local foresters. Accordingly, such interpretations are more art than science, because they depend on the experience and intuitive ability of individual soil scientists and foresters. Probably in many cases these subjective interpretations are satisfactory. However, acceptance of these assumptions is largely a matter of faith until research can provide firm facts baded on carefully collected and analyzed measurements.

Soil-survey reports often list site-index averages for the many soil-taxonomic units described in the soil survey. But these individual averages are frequently based on few actual site measurements. Moreover, close inspection of the basic data often shows that site index varies widely within soil units while, in contrast, the averages of most units are strikingly similar. Thus, the logical conclusion is that similar averages and excessive site variation within soil units often limit the usefulness of soil-taxonomic units for site-quality classification.

Excessive site variation within soil-taxonomic units has been shown for black oak in southeastern Ohio (*13*), for yellow-poplar in southwestern Virginia (*66*), for yellow-poplar and upland oaks in the southern Appalachians (*40*), and for sugar maple in New York.[1] Probably much of this observed site variation is related to certain soil and topographic features that vary widely within soil-taxonomic and soil-mapping units, but may not be well described in the definitions of these units. Such soil and topographic features include surface-soil depth, texture and stone content of the subsoil, slope position and steepness, slope shape, and aspect.

Obviously, if site quality is to be accurately classified, the classification of soil types or soil phases must be based on the soil and topographic features that are closely related to differences in forest-site quality. The many soil-site studies published for hardwoods (tables 2 and 3) and for other forest species (*18,56*) can provide this information. These soil-site studies not only quantitatively pinpoint the significant soil and topographic features, but also express the magnitude of the site changes associated with each of these significant features. Ideally this information should be obtained for each study area before soil surveys are made, so that features closely related to site quality can be included in the definitions of mapping units for the soil survey.

The classification system of soil surveys is flexible and provides for the addition of phases or subdivisions needed to serve the utilitarian objectives of users. Accordingly, designing phases or subdivisions that permit classification of forest-site quality can easily be done once we know the specific soil and topographic features that should be included. But close coordination between soil-site research and soil survey is needed if the most effective breakdown by phases or subdivisions is to be developed.

For example, excessive variation of oak-site quality occurred in the soil-taxonomic units described for upland soils of southeastern Ohio (*13*). Soil-site studies pinpointed the important soil and topographic features that were related to site changes in this area (*14*). These soil-site results were then used as a basis for constructing topographic phases that better defined differences in oak-site quality (*16*).

Soil Site Studies

Forestry research has accumulated much information about relationships between tree growth and features of tree environment including soil, climatic, and topographic features (*18,56*).

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[1]Berglund, J. V. *The utility of the National Cooperative Soil Classification System in the management of New York sugar maple stands.* Unpublished manuscript.

Table 2.—Soil-site studies for upland oaks in the East

Area	Topographic features	Soil features	Reference
Connecticut	Slope position	Total N	Lunt (*44*)
Rhode Island	Slope steepness	Surface soil depth	McGahan et al. (*47*)
		Soil texture	
		Soil drainage	
S. Michigan	Slope position	Subsoil texture	Gysel & Arend (*31*)
	Slope steepness	Subsoil moisture	
NE. Iowa	Aspect	Soil depth	Einspahr & McComb (*24*)
	Slope steepness		
Arkansas Ozarks	Slope position	Soil depth	Arend & Julander (*2*)
	Aspect	Parent material	
SE. Ohio	Slope position	Surface soil depth	Gaiser (*28*)
	Aspect		
SE. Ohio and S. Indiana	Slope position	Surface soil depth	Carmean (*14,16*)
	Aspect	Subsoil texture	and Hannah (*33,34*)
	Slope steepness	Subsoil stone content	
	Slope shape		
Appalachian Mts.	Slope position	Soil depth	Trimble & Weitzman (*64*)
(West Va.)	Aspect	Parent material	Trimble (*63*)
	Slope steepness		Yawney (*69*)
Ridge and Valley	Slope position	Depth of A+B	Yawney & Trimble (*70*)
(W. Va. & Md.)	Aspect	pH of A2	
Appalachian Mts.	Slope position	Surface soil depth	Doolittle (*22*)
(N. Carolina)	Aspect	Surface soil texture	
		Humus type	

Appalachian Mts. (Georgia)	Slope position Aspect Slope steepness Elevation	Surface soil texture	Ike & Huppuch (*40*)
Piedmont (Va., N. & S. Carolina)	Slope position Slope steepness	Org. content of A1	Della-Bianca & Olson (*21*)
N. Alabama	Slope position Slope length Aspect		Smalley (*60*)
N. Mississippi and W. Tennessee	Slope position	Depth to least perm. horizon Surface soil texture 15 atmos. tension of least perm. horizon	McClurkin (*46*)

Table 3.–Soil-site studies for other upland hardwoods in the East

Species and area	Topographic features	Soil features	Reference
Yellow-poplar:			
Central States	Slope position Aspect	Depth of A1 Depth to subsoil Surface soil texture Subsoil drainage	Auten (*4*)
W. Indiana		Depth of A1 Depth to claypan or mottling	Tryon et al. (*65*)
S. Illinois		Depth to fragipan Depth of organic matter	Gilmore et al. (*30*)
New Jersey	Slope position	Depth to mottling Depth to subsoil Subsoil texture	Phillips (*52*)
Piedmont (Va., N. & S. Carolina)	Slope position Latitude	Depth of A1 Organic content of A1 Surface soil texture	Della-Bianca & Olson (*21*)
W. Tennessee	Slope position Aspect	Depth to gley Drainage	Hebb (*37*)
Appalachian Mts. (Georgia)	Slope position Elevation		Ike & Huppuch (*40*)
Sugar maple:			
N. Michigan		Soil depth Soil texture Stone content Drainage	Westveld (*67*)
Vermont	Elevation Aspect Latitude		Post (*55*)

Black walnut:			
Central States (prairie soils)		Surface soil depth Drainage Soil texture	Auten (*3*)
SE. Iowa		Depth A Total soil depth Mottling	Hansen & McComb (*35*)
SE. Iowa		Depth to claypan Soil color pH, Ca, K, N, Mg	Thomson & McComb (*61*)
S. Illinois	Slope position	Depth to mottling	Carmean (*15*)
Black locust:			
Central States (prairie soils)		Surface soil depth Drainage Soil texture	Auten (*3*)
Sweetgum:			
Delaware & Maryland (coastal plain)		Subsoil texture Depth to subsoil	Phillips (*53*)
S. New Jersey		Profile texture Subsoil thickness	Phillips & Markley (*54*)
Mississippi Valley	Slope position	Texture Internal drainage Depth to hardpan K content	Broadfoot & Krinard (*12*)

(continued)

Table 3.—Soil-site studies for other upland hardwoods in the East (continued)

Species and area	Topographic features	Soil features	Reference
Green ash:			
SE. Iowa	Slope position Aspect	Total soil depth Depth to imperious subsoil Past land use, erosion Soil color	Hansen & McComb (*35*)
Cottonwood:			
Mississippi Valley	Slope position	Texture Internal drainage	Broadfoot (*8*)
Willow oak:			
Mississippi Valley & (coastal plain)	Slope position	Texture K content	Beaufait (*5*)
Mississippi Valley & (coastal plain)	Slope position	Texture Depth to mottling or pan	Broadfoot (*11*)
Cherrybark oak:			
Mississippi Valley & coastal plain	Slope position	Surface soil depth Depth to mottling or pan Texture Internal drainage	Broadfoot (*9*)
Water oak:			
Mississippi Valley & Coastal Plain	Slope position	Surface soil depth Depth to mottling or pan Texture Exchangeable Na	Broadfoot (*10*)

Initial emphasis was placed on the southern pines, but now considerable soil-site information is also available for various eastern hardwoods (tables 2 and 3). Most of these studies are based on multiple-regression analysis of site index or of tree height (and tree age) measurements, and associated soil, climatic, and topographic factors. Significant site features pinpointed by these multiple regressions were used to calculate site-prediction tables for the field estimation of site quality. Site-prediction tables developed for a particular area provide a universal means for estimating site quality of all forest lands regardless of the composition or condition of existing vegetal cover. And species-comparison studies enable us to extend these site estimates to other tree species that might be considered for forest management.

Site evaluation based upon soil-site studies permits us to evaluate site only for the local spot in the landscape where we may happen to measure the significant features of soil, topography, or climate. Thus site evaluation still is a point observation comparable to point observations of site index using trees themselves. Still to be resolved is the problem of abstracting these point observations into an area classification of the landscape.

Effective land classification requires the use of aerial photographs and all available information about local soil and topography. Here is where forest managers can best use the skill and knowledge possessed by soil surveyors. Closer future coordination between soil-site research and soil survey can provide land-classification knowledge and techniques useful in forest-land management. Research can pinpoint the features of soil and topography important in classifying forest-land productivity. And soil surveyors can then incorporate this knowledge into soil surveys so as to obtain more useful inventories of forest lands.

Site-prediction tables developed from soil-site studies are applicable only to the particular area studied and, further, to the particular soil and topographic conditions measured within the study area. For example, results obtained for upland oaks in Ohio should not be applied in other states where soil, topography, and climate are different. Likewise, within a particular study area, results for upland soils should not be applied to bottomland soils or to other soil conditions not included in the original site study. Soil conditions of heavily grazed woodlots or of cultivated or abandoned agricultural fields are also different from undisturbed forest soils where most hardwood-site studies are made. Accordingly, soil-site correlations developed from studies of undisturbed forest soils may not be applicable for hardwoods on soils disturbed by agriculture or heavy grazing. For example, foresters who have planted hardwoods in the Central States recognize that site conditions for hardwoods on abandoned fields are different from site conditions in nearby forest stands having undisturbed, but otherwise similar soils.[2]

The large number of soil-site studies listed in tables 2 and 3 appear impressive at first glance. However, we should bear in mind that eastern hardwoods cover a very large area that is extremely diverse in climate, topography, geology, and soil. Furthermore, eastern hardwoods include a large number of tree species that frequently respond in different ways to varying conditions of climate, soil, and topography. Accordingly, it soon becomes apparent that large gaps in our knowledge exist for many forest areas and for many important eastern hardwood species. For example, the northern Appalachian Mountains, the Lake States, and the glaciated portions of the Midwest have received relatively little study. Almost no site information is available for our more valued hardwoods such as black walnut, black cherry, yellow birch, basswood, and white ash.

A review of the many soil-site studies for eastern hardwoods (tables 2 and 3) reveals some general trends about the soil and topographic features frequently associated with site-quality changes. All species of trees apparently respond to favorable site conditions even though the amount of response varies and even though certain tree species are more tolerant than others of unfavorable site conditions. Accordingly, the features found to be closely related to site quality for hardwoods are usually the same soil, topographic, and climate features important for coniferous growth.

Soil conditons most important are generally those that express soil depth, soil texture and stone content, and soil

[2]Carmean, W. H., F. B. Clark, and P. R. Hannah. *Forest trees on abandoned land improve soil conditions and subsequent growth of planted hardwoods.* Unpublished manuscript submitted to Soil Sci. Soc. Amer. Proc. 1969.

drainage—that is, those soil properties " . . .which influence the quality and quantity of growing space for tree roots" (*18*). In general, site quality increases as soil depth increases: trees seem to be particularly affected by depth changes in the surface-soil layers where the majority of tree roots are concentrated. Usually medium-textured soils are the best sites, and site quality decreases for both coarse-textured soils and for fine-textured soils. Site usually decreases as stone content increases, and sometimes as drainage becomes poorer.

Topographic conditions most important are slope position, aspect, slope steepness, slope shape, elevation, and latitude. The best sites usually are found on lower slopes, north and east aspects, and on gentle, concave-shaped slopes. Poorer sites usually are found on narrow ridges and upper slopes, on south and west aspects, and on steep convex-shaped slopes. Obviously, topography can have no direct effect on tree growth; it is, however, closely related to differences in microclimate, soil moisture, and soil development. Accordingly, topography generally serves as an index of materials and conditions required for good tree growth—moisture, nutrients, temperature, and so on.

Even though we can generalize about soil and topographic features related to good tree growth, we find that soil-site studies show considerable variation in site features found to be important. Features important in one area may be unimportant in another. A feature may even show positive trends in one area and a negative correlation with site quality in another area.

One reason for differing results is that tree species vary in their response to differences in soil and topography. This is natural, and we should expect upland oaks to respond differently than black walnut, or than sweetgum or willow oak growing on bottomland alluvial soils. Another reason for differing results is due to differences in study areas. Topography would obviously be far more important in a rough hilly or mountainous area than in areas having flat or rolling topography. Drainage or soil texture would be unimportant in areas where all the soils are well drained and where soils are similar in texture. And areas having coarse-textured soils would usually show increases in site index as the content of silt and clay increased, while in contrast, areas having mostly fine-textured soils usually show decreases in site as texture becomes heavier.

An additional reason for differing results is related to the methods used in statistical analysis. Multiple-regression equations contain those soil and topographic variables that in combination give the most precise estimates of site quality. These equations have much practical value as they can be used to closely estimate site quality by using relatively few features of soil and topography. However, care must be exercised in interpreting the effects of significantly important factors and of those not significant in the regression analyses. Multiple-regression equations usually list site features in the order of their significance—that is, those features closely associated with large changes in site quality are listed first, and factors of less significance in the analysis appear in a secondary position. Thus, the trends expressed for the highly significant site features are very dependable while, in contrast, the trends expressed for the less significant variables often are conditioned by the effects of the stronger variables. This may be particularly true when considerable correlation occurs among the various site features listed in the equation.

Furthermore, we should recognize that many soil and topographic features may be associated with site quality in addition to those that appear in the final regression equation. The many simple correlations between site quality and various individual soil and topographic features are usually evident from scatter diagrams, or from computer screenings used as the first step in regression analyses. However, later regression computations may result in the dropping of many factors that show initial trends—because (1) they are closely correlated to other more significant factors that are retained in the equation, and (2) their retention would not materially improve the accuracy in predicting site quality by the regression equation.

Even though initially promising factors may be dropped during regression analysis, their influence may still be indirectly retained in the final equation. For example, both slope position and soil depth may be closely associated with site quality. However, these two features may also be closely related to each other—that is, deep soils occur on lower slopes and shallow soils on upper slopes. Therefore, a regression equation containing only slope position might adequately express both (1) the moisture and microclimate effects of slope position and (2) indirectly the effects of soil-depth differences that are closely associated with slope position.

Site quality is related to the natural occurrence of hardwood species, as well as to their growth and yield. Certain hardwoods such as upland oaks commonly grow on almost all upland soils and over almost the entire range of site quality. For example, stem-analysis data showed that site index for black oak in southeastern Ohio ranged from a low of 34 feet to a high of 106 feet (*17*). Similar wide ranges in site index were observed for various upland oaks in the Southern Appalachians, in the Blue Ridge Mountains, and in the Virginia-Carolina Piedmont (*40*). In contrast, other hardwood species are much more limited in their occurrence and may be restricted to certain soils or to relatively narrow ranges of site quality. Hardwoods often restricted to the poorer sites include post, blackjack, and chestnut oaks. Hardwoods often restricted to medium and good sites include those valued for furniture and veneer such as yellow-poplar, black walnut, white ash, basswood, and sugar maple.

CONCLUSIONS

Both the quantity and quality of yield for eastern hardwoods vary greatly with site quality. Many hardwoods, such as upland oaks, commonly occur over a wide range of sites while, in contrast, other hardwood species may occur on a relatively narrow range of good or poor site. Generally site is associated with those soil features that determine the quantity and quality of growing space for tree roots. Topographic conditions are important because topography is an index of microclimate and soil conditions required for good tree growth.

Many methods for evaluating site quality for hardwoods exist, but the direct measurement of site index from standing trees is the most dependable—that is, if suitable trees and accurate site-index curves are available. The three indirect methods of estimating site quality are based on plant indicators, soil types, and results from soil-site research. All direct and indirect approaches to site evaluation are useful, and all of these methods are in reality complementary rather than contradictory. Accordingly, the future should show not a segregation into strict lines of soil, ecological, or mensurational disciplines, but a spirit of tolerance, respect, and constructive borrowing and learning from all fields of site evaluation.

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GENETICS AND TREE IMPROVEMENT IN THE OAK—YELLOW-POPLAR TYPE

by CHARLES D. WEBB, *plant geneticist, Forestry Sciences Laboratory, Southeastern Forest Experiment Station, Forest Service, U. S. Department of Agriculture, Athens, Georgia.*

MY DISCUSSION of tree improvement is based upon the realization that genetic tree improvement, as accomplished by selection and breeding, must be combined with intensive silviculture so that trees of the desired quality level can be produced economically. Superior strains of hardwoods must be planted on carefully selected and well-prepared sites, and planting probably should be followed by some form of weed control and fertilization. Also, natural regeneration from sprouts can be relied upon after many hardwood logging operations. Therefore, hardwood planting programs should be restricted to those situations where natural regeneration is either from undesirable species, is inadequate, or is completely lacking.

In this context, I will discuss what we know about genetic variation within the species of the oak–yellow-poplar type, and how much improvement we can expect from selection, breeding, and intensive silviculture. I will concentrate on only a few of the most important species: the oaks, yellow-poplar, black walnut, and sweetgum. Because our knowledge of inheritance within any one species is incomplete, occasional references to other species will fill in gaps in our knowledge.

An important qualification is necessary: most of the results I will discuss are based on trees less than 10 years old. Therefore, the inheritance figures must be considered tentative. Unfortunately, many of the studies established over 10 years ago have suffered from poor survival and site variability.

GENETIC VARIATION WITHIN SPECIES

Geographic Seed Sources

Genetic variation within a species can be separated into differences among geographic seed sources or races, and among individual trees within seed sources. Excepting a few oaks, all the species we are considering have wide geographic distribution: sweetgum grows naturally in 23 states, yellow-poplar in 26, black walnut in 31, and northern red oak in 29 *(U.S. Dep. Agr. 1965)*. These areas include wide ranges of latitude, longitude, and elevation. Against such a diverse environmental background, natural selection has produced racial variation that is economically significant.

The most important and consistent differences among geographic seed sources in hardwoods have appeared in dormancy relationships. The dormancy relationships determine when seedlings from a particular seed source will begin growth in the spring and when they will stop growing in the fall. Upon this depends (1) whether seedlings of a particular source suffer any frost damage, and (2) how efficiently they use the growing season available to them. Racial differences in dormancy are known to exist in yellow-poplar *(Farmer et al. 1967, Sluder 1960, Funk 1958)*, northern red oak *(Kriebel 1965)*, black walnut *(Wright 1954)*, sweetgum[1], sugar maple *(Kriebel 1957)*, and *Populus (Pauley and Perry 1954)*. Definite differences in frost damage have been reported in yellow-poplar *(Funk 1958)*, shumard oak *(Gabriel 1958)*, sugar maple *(Kriebel 1957)*, and ash *(Santamour 1963)*. A general rule has been stated *(Pauley and Perry 1954)*:

> In general, movement from the latitude of the natural habitat northward (i.e. with longer days) prolongs the active period of growth; and movement southward (i.e. with shorter days) shortens it. Such modifications on the length of the active growth period normally result in marked differences in seasonal increment and frost hardiness. Thus, movement of plants into a day-length regime longer than that of the native habitat characteristically gives increased height growth accompanied by decreased

[1]Roberds, James Hall. *Patterns of variation in several characteristics of sweetgum (Liquidambar styraciflua L.) in North Carolina.* Unpublished M.S. thesis, N. C. State Univ. School of Forestry, 1965.

resistance to autumnal frosts; whereas movement into a short-day regime results in dwarfing, associated with increased frost resistance.

Few studies are old enough to permit comparisons of total volumes per acre of different seed sources, but significant differences in early height growth have been reported for several species: yellow-poplar *(Farmer et al. 1967, Thor*[2]*)*, northern red oak *(Kriebel 1965)*, shumard oak *(Gabriel 1958)*, black walnut *(Wright 1954)*, sugar maple *(Kriebel 1963)*, and sycamore *(Fogg 1966)*. A few studies have failed to show significant differences, even among seedlings from sources that are widely separated *(Sluder 1960, Santamour and Schreiner 1961, Schreiner and Santamour 1961, Roberds*[1]*)*.

Racial variation has appeared in other important traits: epicormic sprouting of a European species of oak *(Irgens-Moller 1955)*, apical dominance, forking, and drought tolerance in sugar maple *(Kriebel 1957)*, and cork on seedlings of sweetgum (*Roberds*[1]).

None of the seed-source studies has shown a single, widely adapted source for any of the species studied. The local source has not always produced the best growth. But local sources have been in phase with their environment—they have been frost-resistant to an acceptable degree, and they have efficiently used the growing season available to them. When growth and form are considered, there are notable instances where distant seed sources and individual trees perform exceptionally well. Because these exceptions are encountered in both conifers and hardwoods, a combination of racial, stand, and individual tree selection is recommended for maximum gain in tree-improvement *(Wright 1967)*. Studies should maintain the identity of both family and racial relationships. Results on growth and yield should be considered tentative until the tests have endured some severe years, including hard winters, early and late frosts, hot summers, drought, disease epidemics, and insect outbreaks.

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[2]Personal communication with Dr. Eyvind Thor, Associate Professor, Department of Forestry, University of Tennessee, Knoxville.

Individual Tree Variation

The maximum genetic gain will often be achieved by selecting the best families from certain races and the best individuals from certain families. The success of this approach will depend upon the existence of a wide range of hereditary variation among individual trees. There are conspicuous gaps in our knowledge of inheritance within the species under consideration. Many of these gaps should be filled when the many well-designed studies that have been installed recently are analyzed. But even with the limited knowledge available, it is possible now to come up with some idea of the success we can expect from selection for the different traits.

Our knowledge of inheritance within these species is summarized in table 1. The data come from reports by Wilcox *(1968)* on sweetgum, Taft[3] on yellow-poplar, Kriebel *(1965)* on northern red oak, and Wilcox and Farmer *(1967)* and Schreiner *(1959)* on *Populus.* The data on sycamore and disease resistance of yellow-poplar clones come from our work at Athens, Georgia. The table shows only the approximate degree of hereditary control. Heritability fractions, although simple in concept, are difficult to estimate precisely. Stated generally, heritability is the fraction of the total variation (genetic and environmental) that is controlled by heredity and is available for selection and breeding. The higher the heritability, the easier it is to make progress through selection and breeding.

The most important conclusion to be drawn from this summary is: there is significant and usable genetic variation among individual trees for almost every trait of interest. Genetic control of dormancy relationships is consistently high; and that of branching, crown form, and bole straightness is intermediate. However, genetic control of height and diameter growth is within the low to intermediate range. Clones of *Populus* show very strong differences in resistance to certain diseases; similar differences in pest resistance can be expected in other species. Figures are not available on hereditary control of grain patterns or epicormic branching for these species, but undoubtedly genetic differences in these important traits will appear as trees

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[3]Taft, Kingsley Arter, Jr. *An investigation of the genetics of seedling characteristics of yellow-poplar (Liriodendron tulipifera L.) by means of a diallel crossing scheme.* Unpublished Ph.D. thesis, N. C. State Univ. School of Forestry, 1966.

Table 1.—Relative degree of hereditary control of some economically important traits in several hardwood species

Characteristic	Species				
	Sweetgum	Yellow-poplar	Northern red oak	Sycamore	*Populus* spp. (clones)
Height	L-I[a]	sig.[b]	sig.	VL	I
Diameter	L	—[c]	—	L	I
Branching	I-H	—	—	—	sig.
Crown form	I	—	—	—	—
Straightness	sig.	—	—	—	sig.
Date of bud break	VH	—	—	sig.	VH
Date of leaf-fall or growth cessation	—	sig.	sig.	—	VH
Disease resistance	—	sig.	—	—	VH

[a]Degree of hereditary control:
- VL - very low (h^2 = 0–.2)
- L - low (h^2 = .2–.4)
- I - intermediate (h^2 = .4–.6)
- H - high (h^2 = .6–.8)
- VH - very high (h^2 = .8–1.0)

[b]"Sig." indicates that family differences were significant but no heritability fraction was calculated.

[c]Dash indicates no report available.

in the progeny tests become older.

When these plantations are older and more complete analyses are available, it will be possible to combine the genetic information with data on the relative economic importance of each trait. This will provide a criterion for deciding which traits to improve and how to proceed most efficiently.

EXPECTED PROGRESS

Even in the face of incomplete knowledge on inheritance, numerous programs of applied tree improvement and genetics research are under way in almost every state east of the Mississippi for one or more species of the oak–yellow-poplar type. These programs are supported by private industries, universities, state forestry organizations, TVA, and the U.S.D.A. Forest Service. A complete summary of these programs would require a lengthy report. However, Dorman *(1966)* has summarized both pine and hardwood tree-improvement activities in the South and Southeast. Reports of some of the work under way in the Northeast are found in the proceedings of the 15th Annual Northeastern Forest Tree Improvement Conference.

How much progress can we expect from the action programs for tree improvement that are under way now in the hardwoods? How much can log quality be improved and rotations be shortened? Only highly speculative answers are possible now.

Those action programs that began with restrictive systems for selecting only the best-formed trees from natural stands will probably make appreciable improvements in straightness and self-pruning during the first generation of selection (fig. 1). Early progeny-test results on branching characteristics and straightness attest to this.

How much genetic improvement will be achieved in growth rate will remain a moot question for some time. Because of the highly variable nature of hardwood stands, it is impossible to use refined systems for comparing the growth of candidate trees with growth of their neighbors in the stand. (Yellow-poplar may prove to be an exception.) Consequently, the maximum gains in volume will have to wait until progenies are established in evenly spaced and well-attended plantations. Within these plantations, it will be possible to compare the growth of

Figure 1.—First generation selection will probably achieve substantial improvements in branching, which is related to self-pruning. While the tree shown on the left is not perfect, it exhibits much better self-pruning than the tree on the right.

outstanding individuals with that of their neighbors and with the rest of their family. Our early progeny test results on height and diameter indicate that this will be an effective and necessary procedure for achieving substantial improvements in growth rate.

The consensus is that rotations for high-quality veneer-log production might be shortened in some cases to as low as 30 or 40 years. This shortened rotation will be achieved by growing genetically improved stock on the best sites at wide spacings and by using fertilization, weed control, and possibly pruning.

The gains that the pulp industries will realize from hardwood tree improvement will depend on the acreages planted to hardwoods, and on the type of hardwood pulp required. At present, the pulp industries anticipate only limited hardwood planting because of the expense of artificially regenerating hardwoods and the abundance of natural regeneration from sprouts. This attitude may change as improved hardwood seedlings become available and as we learn more about growing hardwoods.

Some of the hardwoods, however, are capable of producing large volumes of pulpwood on certain sites. For example, our 7-year-old sycamore plantation of unimproved, nursery-run seedlings on a riverbottom old-field site south of Athens, Georgia, has produced an average of 2.06 tons of dry wood per acre per year on unfertilized plots. Plots that received a single application of 150 pounds of nitrogen per acre during the first growing season have averaged 2.29 tons of dry wood per acre per year, and those that received 300 pounds of nitrogen per acre averaged 2.42 tons per acre per year. These yields are comparable to yields reported for certain outstanding families of loblolly pine in the North Carolina State – Industry Cooperative Tree Improvement Program *(1968)*.

We plan to select and propagate the largest and best-formed trees from this sycamore plantation. If the largest trees (upper 10 percent) are put in a clonal seed orchard, gains in individual tree volume should approach 10 percent. However, if these trees are propagated by cuttings, there should be an increase in individual tree volume of about 20 percent. If we speculate further about the application of fertilizers to these selected cuttings, yields could approach 40 to 50 percent greater than those of unimproved, unfertilized stock.

A different type of hardwood pulp will be produced by the proposed silage sycamore concept *(McAlpine et al. 1966).* This controversial concept would combine very short rotations, mechanical harvesting, and repeated coppice regeneration. The proposal has great promise for producing large volumes of certain types of hardwood pulp, and genetically improved strains will play an important part in the success of the concept.

CONCLUSION

Our expanding knowledge of inheritance in forest trees –hardwoods and conifers–shows that we have available a large supply of genetic variation in growth rate, tree quality, and pest resistance. I am confident that careful selection and breeding, when combined with good silviculture, will be effective in economically producing high-quality veneer logs and high volumes of pulpwood.

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