REVIEW ARTICLE

*J. For.* 117(1):55–64
doi: 10.1093/jofore/fvy053
Published by Oxford University Press on behalf of the Society of American Foresters 2018.


history

# History, Highlights, and Perspectives of Southern Upland Hardwood Silviculture Research

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**Field trials to quantify the long-term effect of silvicultural treatments in southern upland hardwood forests began on USDA Forest Service Experimental Forests and Ranges nearly 100 years ago. Many of those outdoor laboratories and the research sites they contain are still being examined by Forest Service scientists and their cooperators. The original field experiments began with a well-documented manipulation of stand density, structure, and composition so that scientists could monitor changes in forest characteristics for many decades. Although the original focus of the early studies was on tree growth and water quality, their research value for studying dynamics in wildlife habitat, forest health, recreation, and ecosystem function expanded exponentially with each passing decade. This report highlights early published results from many of the Experimental Forests and related sites located in the South that are pertinent to current and emerging upland hardwood forest-management issues.**

**Keywords:** Upland hardwoods, research, Southern region, management

The silvic requirements of upland hardwood tree species have changed little, if at all, over the last century, but the expectations surrounding their assemblages and outputs, and the silviculture required to meet those expectations, have undergone several evolutions. Upland hardwood silviculture research in the southern United States has mirrored those changes, bounded by constraints of time and other resources. Not only have the outputs associated with sound hardwood management changed from primarily production-based to more multiple use, but also the ownerships and influences have shifted. Unfortunately, even under a constant bureaucracy such as the USDA Forest Service, long-term studies in hardwood systems are not widely found. A complete rotation of 100 years for a hardwood forest, give or take a decade, does not meld with the career sequence of a hardwood forest researcher.

As society changed, the research arena adjusted, shifting from demonstration plot-focused studies toward more stand- and landscape-level projects. Computing power contributed greatly to these changes, as did exponentially increasing opportunities to publish and disseminate research results. However, it is interesting to note that the topics germane to hardwood silviculture have not changed much over time; analysis of data for specific outputs, such as growth and yield, has waned, but applications of even-aged and uneven-aged prescriptions, and intermediate stand treatments such as fire or herbicides, appear to cycle.

Based on my review of upland hardwood research, I suggest that early research is still valuable and still should be consulted. Too often, this early research is overlooked, and we pose questions that others have already addressed. Here I argue that the need for continued research is paramount—from creating early successional habitat (using prescriptions such as clearcutting as well as others) to predicting species distribution to climate change (what we would call a disturbance); we are still relevant. And within today's constraints of resources, we need to build on past studies and results, and reduce redundancy.

This review of the early literature of Southern upland hardwood research focused broadly geographically, essentially capturing work conducted in the Tennessee River Valley. Any area with topographic relief and hardwood forests was considered; a few additional research outputs from outside the region were included because of their influence on progressing Southern hardwood research. The overarching goal of this body of research can be summarized as sustaining oak (*Quercus* spp.) forests. In 1860, David Henry Thoreau stated "The time will soon come, if it has not already, when we shall have to take special pains to secure and encourage the growth of the white oaks . . ." (Foster 1999, p. 94). In 1961, Carvell and Tryon (p. 98) stated, "The deficiency of oak regeneration beneath mature oak stands is

Received February 7, 2018; accepted October 4, 2018; published online November 15, 2018.

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of grave concern to the forest manager since oak regeneration is virtually impossible to obtain quickly." The explosion of work connected to regenerating oak forests is readily available and includes myriad oak-centric proceedings (Table 1). By 1993, Loftis and McGee (1993, p. 319) reported ". . . scientists will provide answers to biological questions so that it is likely that oak regeneration in the future will be limited by economic and social constraints." Today, however, we still struggle to write a prescription to regenerate oak on our most productive upland sites.

## In the Beginning

One of the earliest reports on Southern upland forests came from Raphael Zon in a US Department of Agriculture Forest Service Circular in 1907 (Zon 1907). Zon's title was "Chief- Office of Silvics," and he reported to Gifford Pinchot, whose title was simply "Forester." Pinchot's early connections with the Vanderbilt family in the mountains of North Carolina most likely influenced his interest in this region. Zon's report, "Management of Second Growth in Southern Appalachians," was geared towards sustaining timber supply. He noted that the wooded area of the Southern Appalachians was 80–85% second growth, had resulted from clearcutting for charcoal, ties, and timber mines, and was even-aged. His concern was that unless improvements were made in the methods (management) of handling these lands, the future yield would be both small in quantity and poor in quality. The changes that he outlined were, first, a closer economy in the use of the forest (resources), in which he focused on utilization and waste reduction, giving concrete examples of the amount of waste in the cutting of ties and detailing this in three tables. As coppice forests were expected, Zon suggested conducting careful logging done in the spring and winter with cuts made low on the stump, because sprouts originating higher on the stump were prone to fire damage and served as conduits for rot. Second, he compelled enhanced adaptation of species and sizes to specific uses (products), with examples using American chestnut (*Castanea dentata* [Marsh.] Borkh.), yellow poplar (*Liriodendron tulipifera* L.), and white oak (*Q. alba* L.). Coppice forestry was most successful with smaller diameter timber, which sprouted more readily than larger-diameter trees, and he raised concerns over needing longer rotations in order to have timber of large dimensions. He provided data showing that small stumps had a greater propensity to sprout than larger stumps, and the black, scarlet, and red oak sprouted more reliably than white oak. Finally, protection of the forest, with a nod towards protection from grazing and especially fire, was warranted. He emphatically concluded that light was the most important limited factor, over soil and moisture conditions. His management recommendation was true "selection forestry" upon which ". . . the basis of the next cut should be left . . . at each logging in the form of well advanced sapling and polewood (coppice and seedling origin) . . ." (Zon 1907, p. 14).

In the Tennessee River Valley, after 40 years of annual fire, Zon noted that oak sprouting was being exhausted, and reproduction "of any character" was scarce. In upland hardwood forests, fires were often accidentally set, had cultural impetus, and were not used as a forest-management tool, except in instances where log debris was burned to clear areas for access. The vast Western US wildfires of 1910 and subsequent implementation of US Forest Service forest policy to combat fire contributed to researchers' negative attitude regarding fire in hardwood forests. Zon's concern over the adverse effect fire was having on the composition and structure of the forest was evidenced in table 8 (Zon 1907), in which he showed the growth of sprouts under badly burned and slightly burned scenarios; of interest to note is the language used to describe the fires and the lack of an unburned comparison. At that time in the southeast, little effort was made to keep fire out of the forest, and Zon lamented, "Protection against fire is essential to conservative forest management in the Southern Appalachians" (Zon 1907, p. 21). He ended his report by concluding, "The people should be educated to respect the rights of the timberland owner and should be brought to see that the prevention of forest fires and of unrestricted grazing is for the best interest of all" (p. 21).

Following Zon's report was a survey and report by Earl Frothingham addressing the cut-over areas in the Southern Appalachians (1917). Frothingham, whose titles included "Forest Assistant," "Forest Examiner," and "Silviculturist," wrote this report for US Forest Service Chief Graves. Frothingham eventually became the Director of the Appalachian Forest Experiment Station in 1921. He spent 12 weeks in July to September 1915 in the field with J.H. Pottinger, where they surveyed Pisgah, Mt. Mitchell, Unaka, Massanutten, and Monongahela purchase areas. He referred to this work as a silvicultural reconnaissance and truncated his survey because he came to realize that "Observational studies of cut-over areas have the greatest disadvantage of missing the most important stages in the reproduction . . ." (p. 2). He surmised that the precise reasons for the occurrence of a given kind of reproduction after a cutting could only be known if the conditions or disturbances were accurately noted at the time of cutting and thereafter, and suggested that a research approach ". . . to carry out such a program fully would also necessitate incidental studies on seed,

## Management and Policy Implications

Sharing stories has always been a strong Southern tradition. Sharing past research ventures is vital, and the history of collaboration among US Forest Service researchers, university personnel, state agencies, and others is strong for upland hardwood forests in the South. There exists a collective tolerance of respect, borrowing, and learning. In the face of the heightened interest in hardwood management, silviculturists and other managers are turning to past stand histories to understand and direct future management practices. They are also using prior research findings, although it is uncommon for work to be referenced older than a few decades. Rotation length for most southern upland hardwood stands can span 50–150 years, so it would be of benefit to delve deeper into the historic research results. Research from the 1940s touted the use of a shelterwood prescription to regeneration oaks, for example, and many researchers continue to test this 80 years later. Access to older publications has become relatively easy so that sharing those stories is more practical.

**Table 1. Key synthesis publications from 1970 to present addressing upland oak silviculture in the Eastern US.**

| Year | Title | Sponsors | Meeting date and location | Editor(s) | Citation | Papers and first author affiliation |
|---|---|---|---|---|---|---|
| 1970 | *The silviculture of oaks and associated species* | SAF; USFS R&D | October 1968, Philadelphia, PA | | USDA Forest Service, Research Paper NE-144, Northeastern Forest Experiment Station, Upper Darby, PA. 66 p. | 5 papers; 4 USFS R&D; 1 Univ. |
| 1970 | *Proceedings of Symposium on Southern Appalachian Hardwoods* | USFS S&PF; USFS R&D; NC Forest Service | September 22–23, 1970, Asheville, NC | | USDA Forest Service, SA-4, Southeast Area State and Private Forestry, Atlanta, GA. 136 p. | 12 papers; 1 Univ.; 2 State; 4 USFS S&PF; 5 USFS R&D |
| 1971 | *Oak Symposium Proceedings* | USFS R&D; WV Univ.; Appalachian Hardwood Manufacturers; WV Department Natural Resources | August 16–20, 1971, Morgantown, WV | | USDA Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA. 162 p. | 25 papers; 12 USFS R&D; 6 Univ.; 3 Industry; 2 USFS S&PF; I State; 1 USFS NFS |
| 1971 | *Proceedings—Symposium on Southeastern Hardwoods* | USFS S&PF; USFS R&D | September 15–16, Dothan, AL | | USDA Forest Service, Southeast Area State and Private Forestry, Atlanta, GA. 102 p. | 10 papers; 5 USFS R&D; 2 Univ.; 2 Industry; 1 USFS S&PF |
| 1975 | *Silviculture is growing trees* | USFS S&PF; USFS R&D | brochure | | USDA Forest Service, Northeast Area State and Private Forestry, Northcentral Forest Experiment Station, Northeastern Forest Experiment Station, Washington, DC. 8 p. | |
| 1977 | *The scientific base for silviculture and management decision in the National Forest system: selected papers* | USFS R&D | March 22–23, 1976, Washington, DC | | USDA Forest Service, GPO-912-715, Washington, DC. 59 p. | 6 papers; 6 USFS R&D |
| 1979 | *Silvicultural guidelines for forest owners in Georgia* | GA Forestry Commission, GA SAF | | | Georgia Forest Research Paper 6, Georgia Chapter of the Society of American Foresters, Georgia Forestry Commission, Macon, GA. 35 p. | 12 papers; 6 USFS R&D; 3 consultants;1 USFS NFS; 1 Univ.; 1 State |
| 1979 | *Proceedings Regenerating Oaks in Upland Hardwood Forests* | Purdue University; IN Cooperative Extension Service | February 22–23, 1979, West Lafayette, IN | Holt, H.A.; Fischer, B.C., eds. | The 1979 John. S. Wright Forestry Conference, Purdue Research Foundation, Purdue Univ., West Lafayette, IN. 132 p. | 15 papers: 9 USFS R&D; 5 Univ.; 1 USFS S&PF |
| 1979 | *The shelterwood regeneration method. Proceedings of the National Silviculture Workshop* | USFS Washington Office; USFS NFS; USFS R&D; Westvaco Timberlands Division | September 17–21, 1979, Charleston, SC | Cramsey, D.; Puuri, C.; Miller, D.; Page, B.E.; Smith, D.; and 19 others, eds. | USDA Forest Service, Timber Management, Washington, DC. 288 p. | 22 papers: 9 USFS NFS; 7 USFS S&PF; 3 USFS WO; 2 USFS S&PF; 1 Univ. |
| 1980 | *Proceedings Mid-South upland hardwood symposium for the practicing forester and land manager* | USFS R&D; USFS S&PF; AR Forestry Commission; TN Div. of Forestry; Univ. of AR-Extension | April 30-May 2, 1980 Harrison, AR | | USDA Forest Service, Tech. Pub. SA-TP-12, Southeastern State and Private Forestry, Atlanta, GA. 186 p. | 21 papers: 10 USFS R&D; 3 USFS S&PF; 3 Univ.; 3 State; 1 Industry; 1 Consultant |
| 1993 | *Oak regeneration: serious problems, practical recommendations. Symposium proceedings* | USFS R&D; USFS SPF; USFS NFS; Univ. of TN | September 8–10, 1992, Knoxville, TN | Loftis, D.L.; McGee, C.E., eds. | USDA Forest Service, Gen. Tech. Rep. SE-84, Southeastern Forest Experiment Station. Asheville, NC. 319 p. | 26 papers: 15 USFS R&D; 8 Univ.; 2 USFS S&PF; 1 Other (Canada R&D) |
| 1997 | *25 years of hardwood silviculture: a look back and a look ahead. Proceedings of the Twenty-Fifth Annual Hardwood Symposium* | National Hardwood Lumber Association; USFS R&D | May 7–10, 1997, Cashiers, NC | Meyer, D.A., ed. | ISSN 0193-8495, National Hardwood Lumber Association, Memphis, TN. 169 p. | 17 papers; 8 USFS R&D; 7 Univ.; 2 Industry |
| 2004 | *Upland Oak Ecology Symposium: History, Current Conditions, and Sustainability* | AR State (Forestry and Game and Fish); AR Wildlife Fed.; Univ. AR; USFS R&D; | October 7–10, 2002, Fayetteville, AR | Spetich, M.A., ed. | USDA Forest Service, Gen. Tech. Rep. SRS-73, Southern Research Station, Asheville, NC. 311 p. | 51 papers; 21 USFS R&D; 21 Univ.; 4 State; 2 USFS NFS; 2 USFS SPF; 1 USGS |

*Note:* SAF: Society of American Foresters; State: State Forestry Agencies; Univ.: University; USFS NFS: US Forest Service National Forest System; USFS R&D: US Forest Service Research and Development/Experiment Station; USFS S&PF: US Forest Service State and Private Forestry; USGS: USDI Geological Survey.

growth rates, and hardiness of timber species which would require lab work. Even without a large expenditure, more reliable results would come from permanent sample plot study" (p. 3).

According to Frothingham (1917), although the effects from fire and grazing could be "traced back," there was "no sure way of telling" the conditions dictating seed supply, climate, soil, and shading environments. Conditions favoring yellow poplar were prevalent and included exposed mineral soil, elimination of early competition, elimination of overhead shade, and a seed source. For other species, however, he suggested that more intensive study by means of permanent sample plots be established when an area is cut over. Some of the questions he posed were:

> What was on the area before cutting?
> What was cut and what left standing?
> What came up as dominant young growth?
> What are its future prospects?
> What method of cutting would have given better results, and why?

Both of these reports (Zon 1907, Frothingham 1917) noted how the omnipresence of disturbance, including fire and grazing, along with indiscriminant logging and the leaving of poor-quality residuals, has resulted in second-growth forests that needed management to sustain the timber demand. Frothingham (1917, p. 13) said, "Recurrent surface fires have badly injured the timber and the forest floor . . . and . . . (fire) is hardly to be recommended until experiments have thoroughly demonstrated its superiority to clearcutting and girdling without burning." The desired species were primarily yellow poplar and the oaks, with oaks especially valued for mine timbers, and clearcutting on upper slopes in late fall was favored for sprout-producing species such as chestnut and small oaks. Interesting is the same elegy heard today: "Management of the relatively even-aged second growth . . . is hardly likely on account of lack of funds for purely silvicultural work not resulting in immediate income" (Frothingham 1917, p. 20).

The most important result of Frothingham's (1917) study was his conclusion that total clearing or clearing with reserves was needed for an immediate start in the shape of stocked stands of desirable species composition. He recognized the need to control light in order to recruit oaks into competitive positons and recommended thinning where white oak was found overtopped by black and scarlet oak. Shelterwood cutting and selection cutting were also considered, but little thought was given to present or future management of young growth or to the reproduction status and composition. Frothingham noted the spread of the American chestnut blight to the southern Appalachians as "probable" and reported that there needed to be measures to replace chestnut with other species. Until then, he recommended managing chestnut sprouts to secure at least one rotation before the blight; and he stated that isolated populations may remain immune longer, and in these chestnut production should be encouraged. Radical measures would be needed to convert the dead chestnut stands, and he suggested clearcutting in the summer to minimize sprouting. No radical measures were mentioned with regard to slowing the blight's spread or saving existing trees or seed sources.

As a background to nascent silviculture research was the Industrialization Period, roughly from 1861 to 1929, when the production of forest products tripled and the 1924 Clarke–McNary Act added timber production as a National Forest mandate (Hicks 1997). The demand for timber was huge because of a booming economy, population growth, and the infrastructure associated with that growth. Frothingham (1921) addressed this need via yield forecasts that he noted were handicapped by complex forest types, including "hemlock type," "poplar type," and "American chestnut-oak type." He defended this work by asserting that data from one region may or may not be applicable to other regions, but some correlation was warranted. He ended his paper with this quote, an early nod to developing models, ". . . it is proposed as a means of getting something at once which we could hardly hope to obtain otherwise for a long time." (p. 14).

## Silviculture to Address Degraded Stands: Shelterwoods, Light, Fire

For researchers who have devoted careers to studying oak, an original and fundamental reference is work conducted by Clarence Korstian (1927). His earliest work was a cooperative project between the Appalachian Forest Experiment Station and the School of Forestry at Yale. He began by saying ". . . there is little information available upon the seed and seedling characteristics of the American oaks." (p. 7). Research by both the US Forest Service Appalachian and Northeastern Forest Experiment Stations indicated that American chestnut was being replaced by stands higher stocked with various species of oak (Leffelman and Hawley 1925, Korstian and Stickel 1927). The economic importance of oak was gaining, and oak seed sources were readily available. Korstian (1927) continued the mantra that oak sprouts were less desirable reproduction because of increased decay (because of basal fire damage and parent decay transmission) and because the wide spacing of trees that would provide stumps was too great to provide adequate stocking. Korstian (1927) considered artificial regeneration of oak, both by planting and by direct sowing of seed, but recommended natural regeneration of oak by partial harvesting or a two- or three-cut shelterwood method. His conclusions were complemented by those of Leffelman and Hawley (1925), whose work in Connecticut hardwoods also concluded that the desired reproduction (oaks) originates prior to the regeneration harvest, and was assisted in its development under shelterwood prescriptions.

Another seminal research census presented by Buell (1928) addressed the silviculture needed to treat cut-over upland hardwood stands. He recognized that the resultant stands after cutting were dependent on inherent site factors such as forest type and species composition, soil moisture, and previous treatment or disturbance. Light as a factor to control growth was duly noted, and reproduction under the highest light was in larger size classes (4-inch dbh). Seedlings were preferred over sprouts because of their perceived higher resistance to butt rot and windthrow. Sprouting was greater from the less desirable species (red maple [*Acer rubrum* L.], blackgum [*Nyssa sylvatica* Marsh.], American chestnut) than from the desirable lumber species (oaks and yellow poplar), and prescriptions were needed to target both the desired composition and structure of the future stand, not just obtaining reproduction. At this time, although little research existed pertaining to fire in hardwood forests, Buell stated "The first principle of wise use, control of fire is so well proved that it needs no comment"

(p. 212). This sentiment was echoed in a report by Zon and Scholz (1929), in which they reported that repeated fire may delay regrowth of a stand indefinitely.

Research in the 1930s focused on yellow poplar; the primary management was clearcutting to obtain yellow-poplar regeneration, and intermediate treatments of cleaning and thinning were suggested as a need to maintain other desired species such as oaks (Korstian and MacKinney 1931, Sims 1932, Abell 1935). Intermediate stand treatments of thinning and cleanings were used to move the species composition towards the desired species and also to increase growth by eliminating competition for desirable trees. In the Southern US, fire was being used in research to elucidate its effects on timber quality, as well as its role in establishing desired species. The outstanding value of yellow poplar for timber production in the southern Appalachian region (Paul and Norton 1936) aroused interest in the practicability of establishing it by planting seedlings or sowing seed. Studies that examined planting of yellow-poplar seed on cut-over areas or on old field sites showed that it did quite well in these open conditions and suggested that the planting was superior to sowing seeds (Korstian and MacKinney 1931). Another study found that fire was not necessary to obtain adequate stocking of yellow poplar (Sims 1932). One of the earliest studies addressing the effects of fire resulted in data that showed the relation between tree size and mortality caused by fire for American chestnut and oaks (McCarthy and Sims 1935). Their study showed that smaller saplings, 3 inches dbh and smaller, suffered the most mortality with fire, and that susceptibility depended on bark thickness, fire intensity and duration, and crown height above ground level. Another study of 5,882 cut and scaled trees showed that trees wounded at the base had 10 times the amount of butt rot, and 97% of those basal wounds were caused by fire (Hepting and Hedgcock 1935). In their sample, 67% of trees with basal fire wounds had butt rot, whereas only 6% of trees without basal wounds had butt rot. These stands were mainly of seedling origin, and they concluded that butt rot in sprout-origin stands occurs independently of fire scars. Roth and Sleeth (1939) confirmed this, reporting that 10–40% of oak sprouts were butt-rotted as a result of decay transmission from parent stump to sprout, and the incidence of butt rot was positively correlated with height of sprout origin on the parent stump.

## Partial Harvest: Selection Method and Timber Stand Improvement

By 1940, half of the southern Appalachian hardwood stands were less than 40 years old (Downs 1942). A perfect storm of disturbances resulted in stands that were dominated by oaks—chestnut blight, fire, indiscriminant logging, grazing. Silviculture prescriptions were dominated by harvest and residual volumes, and partial harvesting was beginning to be referred to as the selection method for uneven-aged management (Jemison and Schumacher 1948), although the practice more closely mimicked high-grading or diameter-limit cutting. Emphasis was placed on utilization and volume, and loss because of sprouting habits was noted. However, several papers began to address the need to create or sustain habitat, mainly for game animals (Downs 1942, Keetch 1944). During the 1940s, the number of studies that applied a systematic approach (before and after treatment data collection, for example) increased, and many of those studies were key for long-term research results.

Cultural practices in young, second-growth stands received heightened attention as managers realized some effort was needed to improve composition and growth of residual stands, which were dominated by sprout-origin reproduction (Downs 1942, Buell 1943, Keetch 1944). Studies addressing sprout management showed that the season of cutting could help control sprouts of undesirable species (Buell 1940); tending treatments to reduce oak sprouts on a stump when a stand was less than 20 years old reduced the incidence of butt rot (Hepting 1940, Roth and Hepting 1943); and volume was saved by thinning sprout clumps to one low-origin sprout (Downs 1947). In a replicated study followed over 4 years, Downs (1942) justified the expense of weeding of selected crop trees such as sugar maple (*A. saccharum* Marsh.), white oak, yellow poplar, cucumbertree (*Magnolia acuminata* L.), and northern red oak (*Q. rubra* L.) in stands less than 14 years old by stimulated diameter growth, increased height growth, and reduced mortality. The passage of the Knutson–Vandenberg Act in 1930 coupled with the establishment of the Civil Conservation Corps in 1933 gave rise to resources for cultural practices in the National Forests. Under these provisions, a timber stand improvement project on 28 upland hardwood stands in WV, VA, KY, TN, NC, and SC resulted in an increase in the number of dominant desirable timber trees (crop trees), and provided insight on the behavior of felled and girdled trees (Buell 1943).

Depleted and defective stands, because of partial cutting, fire, and disease (chestnut blight), or those stands inherently of a poorer quality because of site productivity were targeted for replacement, improvement, or rehabilitation (Frothingham 1943). A study implemented in the mid-1930s lent insight into silviculture prescriptions needed to "rehabilitate degraded stands" (Jemison 1946), with the primary goal of increasing timber value. This study acknowledged that these stands had not fully recovered from previous abuse, but still contained desirable species and were overmature. How to effectively rehabilitate these stands was studied via: (1) diameter limit cutting all trees greater than 15 inches dbh; (2) quality cut, in which all undesirable (poor form, defective, or less desired timber species) trees are removed; (3) clearcut, with brush mowed before logging; (4) checking, untreated control. Improvement in composition as indicated by the basal area growth was best for the quality cut and clearcut, but the number of less desirable trees in the understory in these treatments was double that of the diameter-limit and check treatments. No specifics were given by species, just broad groups. In 1946, the clearcut was given its first cleaning, and selected crop trees of oak, hickory (*Carya* spp.), yellow poplar, and sweet birch (*Betula lenta* L.) were mechanically released, leaving 250 crop trees per acre. In summary, intensive management was needed to improve these degraded stands, and concern over the composition of the understory, or regeneration, was surfacing.

Downs and McQuilkin (1944), in a seminal paper, focused on defining silviculture prescriptions to sustaining oak stands using "quantitative evidence," with emphasis on the regeneration cohort. Seeding habits, seed fate, and the amount of seed needed for adequate restocking were quantified for northern red, black, scarlet, white, and chestnut oak, and cutting methods were described to enhance seedling growth. They found that some form of partial cutting benefited oak regeneration as litter and canopy cover retarded acorn desiccation, partial shade lent to sapling recruitment, and oak seed sources from trees with healthy, well-developed crowns were plentiful. They referenced partial-cutting systems, including shelterwood and selective cutting. Their results did not support uneven-aged management for oaks, as the conditions following individual tree selection were not favorable for oak growth and recruitment. Group cuttings were reliant on adequate advanced reproduction, which was constrained under this prescription by stand openings and acorn dispersal. They specifically detailed the two-cut shelterwood method, in which the first cut creates conditions for seed germination and sapling growth, and the second cut then releases those trees. Kramer and Decker (1944) had reported that oaks reached maximum photosynthesis at one-third of full sunlight, which would be created by some partial stand openings.

A prominent eastern hardwood forest cover type was forever changed by 1950 (Braun 1950). After 50 years of American chestnut blight, most of the dead trees had been cut, oaks took over the growing space, and forest type classification changed from oak–chestnut to oak–hickory (Keever 1953, Beattie and Diller 1954, Nelson 1955, Woods and Shanks 1957). The slow decline and subsequent gradual removal of American chestnut trees from these stands most likely created conditions conducive to oak, as oak germinants were initially supplied with increased light from the dead overstory American chestnuts, and then released into the sapling layer upon the chestnuts' removal via death or harvest.

## Desirable Regeneration (Oak) Concerns

Research continued on second growth management, productivity, and timber. Soil and topography were being used to develop more site-specific site index curves and yield tables, especially for the upland oaks (Campbell 1951, Trimble and Weitzman 1956, Doolittle 1957, Olson 1959). Partial harvesting resulted in stands composed of smaller logs with lower grades, whereas lumber production costs were rising. One study estimated that 75% of the rot in southern hardwoods was due to fire and found that the proportion of the butt log that had to be culled for rot increased with scar length (Hedlund 1959).

Rehabilitating degraded stands, and the importance of regeneration or advance reproduction for the next stands took on heightened research interest. The rehabilitation study of the 1940s (Jemison 1946) was revisited (Wahlenberg 1953), with a slight modification of the treatment names; diameter-limit cut was repurposed as a flexible diameter-limit (cut 40% of the total volume); the quality cut changed to selection (cut 61% of volume); check renamed control; and clear (cut 100% of volume, with noted economics of sapling removal and mowing [Jansen and Wilson 1951]). The 20-year results showed the same trend as that found earlier: essentially that the greater the disturbance, or heavier the cut, the greater the growth of desirable species. Although the diameter-limit and selection cut had almost equal growth, selection cutting was deemed superior because fewer understory trees were overtopped than the diameter-limit understory, stand quality as indicated by species composition was better, and it had greater saw timber production (Wahlenberg 1953, Wahlenberg 1956). These results supported the viability of single tree selection in these stands, although only one entry had been made.

Another study coming to fruition after 32 years examined "harvest cutting" in mixed hardwood stands in eastern KY (Sander and Williamson 1957). They found that 32 years after clearcutting, when stem exclusion was complete, the stand retained the same percentage of red oak in the overstory but that red oak was not regenerating. Their data showed that large oak was losing out to yellow poplar and sugar maple, with 0–10 stems per acre of oak in the 4-inch dbh and larger size classes, compared with hundreds for yellow poplar and sugar maple. Others were reporting species composition changes away from oak towards red maple and hickory (Keever 1953, Larsen 1953, Nelson 1955, Scholz and DeVriend 1957). Concern rose over how to regenerate oak on these upland sites, and awareness was increasing that clearcutting (also referred to as a "one cut shelterwood" [Tryon and Carvell 1958]) may change stand species composition and did not result in adequate oak regeneration, especially on more productive sites. Awareness grew in that the abundance of oak under the "one cut shelterwood" was not resulting in oak regeneration of competitive size classes—most oak were less than 1 foot tall, and the number of larger oak needed to fully stock a new stand was not known. The sustainability of selection management after 20–30 years was questioned, in that the level of harvesting needed to feed the timber market was in conflict with the projected less desirable species that were dominating the understories in these stands (Weitzman and Trimble 1957).

The 1960s was the beginning of the Environmental Era, with intensified regard as to the use and abuse of natural resources. In 1962, Rachel Carson published *The Silent Spring*, which decried the use of the pesticides that killed wildlife. This widely read book made many Americans first aware that there were limits to what industrial use of chemicals could do to the environment—a term not many Americans were familiar with in 1962 (Carson 1987). Congress passed the Clean Air Act (1963), the Wilderness Act (1964), and the Water Quality Control Act (1965), ushering in the Environmental Era. And although Forest Service managers argued that they had been practicing multiple use, with timber as the primary use, the Multiple Use and Sustained Yield Act of 1960 mandated this. The Act stipulated that the National Forests are established and shall be administered for outdoor recreation, range, timber, watershed, and wildlife and fish purposes. Economic return was not to be the limiting factor in all cases.

Research in the 1960s continued on site index curves (Trimble 1964, Smalley 1967), tree quality (Trimble 1965, Lucas 1969) and diameter distributions (Trimble 1960, McGee and Della-Bianca 1967). Scrutiny continued over clearcutting across the upland oak forest type (Gammon et al. 1960, Walters 1963). More research addressed how to maintain oak in these systems, and although the semantics decreed selection cutting and selection logging, the practices in the forest were regressing into high grading. Other prominent issues included the use of herbicides as a forest-management tool (Sluder 1961, Romander 1965, Little and Somes 1968), and more interest in public use and wildlife concerns (Seely 1960, Della-Bianca 1969).

Oak regeneration was declared as the primary forest-management concern, with researchers and managers realizing that oak regeneration was a process, not a single disturbance/harvest event. Controlling light to the understory was accepted as the principal driver to obtain adequate oak regeneration (Carvell and Tryon 1961, Trimble and Tryon 1966, Carvell 1967, McGee 1968). Even-aged management, especially clearcutting, could be used to regenerate oak, but the oak seedlings would need release from competition, and would grow quickly, especially oak sprouts. It was accepted that the composition of the new stand was highly related to the composition and status of the understory at the time of canopy removal (Bey 1964).

Ben Roach, renowned research silviculturist with the Northern Research Experiment Station, wrote about the moral and biological matters of clearcutting in the late 1960s (Roach 1968). Roach essentially detailed how heavy cutting and uncontrolled fires of the early 1900s led the public to have discord for clearcutting, and that those not in the profession liked selection cutting, related to the sound of the term and to the perceived favorable aesthetics, unaware of the negative biological legacy selection cutting left. Another viewpoint was that selection cutting could provide a sustainable source of valuable logs for industry, even if not at the volume of clearcutting. However, as the eastern forest was just reaching maturity from the previous decades of disturbance, coupled with research results showing selection harvesting or single tree selection in hardwoods did not sustain desirable species, alternatives had to be considered. The terms group selection or patch clearcut and single tree selection became more commonly used to describe any partial harvest (Carvell 1967). However, even though the partially harvested stands continued to grow, recruitment of the valuable species in the smaller-diameter classes was lacking, and more intensive practices would be needed to maintain oak (Minckler et al. 1961, Minckler and Woerheide 1965, Trimble and Tryon 1966).

For National Forests in the East, clearcutting would soon become taboo. Prior to Hurricane Camille, clearcutting in the mountainous areas of the Monongahela National Forest was a common practice on National Forest and private lands. When the storm came through the Monongahela, sedimentation of forest streams at clearcut sites stirred public sentiment and led to a federal lawsuit against the Forest Service for its practice of clearcutting. The decision by the US Fourth Circuit Court of Appeals was to halt all US Forest Service clearcutting in the four-state Fourth Circuit, *West Virginia Division of the Izaak Walton League of America, Inc. v. Butz* (367 F. Supp. 422, 522 F.2d 945 1975). This decision, which came close on the heels of the Bitterroot National Forest clearcutting controversy in Montana, led to a virtual landslide of clearcutting court cases elsewhere in the country. These court decisions set the stage for passage of the National Forest Management Act of 1976 (16 USC. Sec. 1600 et seq.) that required National Forest plans based on public participation, regulation of controversial practices, and an economic analysis component. As Roach concluded, "Nowadays we cannot practice forestry in a vacuum" (Roach 1968, p. 14).

In 1961, Carvell and Tryon detailed the response of oak under various environmental factors in an inclusive examination of influences to oak regeneration (Carvell and Tryon 1961). They showed that oak reproduction was best on drier sites and thus its ease in maintaining it there, as opposed to moister exposures, in which myriad factors increased the competition for light, including more competition from herbaceous vegetation, shrubs and tolerant tree species, and denser overhead canopies. The amount of sunlight in the understory was the driving factor to oak seedling abundance, and subsequent recruitment into the larger size classes. In concert with knowledge of the past disturbances prevalent in oak stands, they used a point system to rank the amount of prior disturbance to a stand and related that disturbance to the amount of oak seedlings. They reported that sites with the greatest amount of previous disturbance (grazing, fire, and logging operations) had the highest abundance of oak seedlings, related to openings that allowed more light to the understory (logging and/or fire) or less competition (grazing preferences and low palatability of oak). They concluded that the ability of oak regeneration to persist was more related to environmental conditions than its ability to become established, because overstory seed sources were abundant, and understory conditions were not retarding germination. Finally, they suggested a series of thinnings during the last years of a stand's rotation to get light to the small seedlings, allowing those seedlings to grow into a more competitive position, prior to overstory removal. This is essentially the shelterwood prescription touted to regenerate oaks that is still under examination today (Janzen and Hodges 1987, Loftis 1990a, Loftis 1990b, Lockhart et al. 2000, Brose et al. 2008, Parker and Dey 2008, Schweitzer and Dey 2011, Parrott et al. 2012, Craig et al. 2014, Miller 2014, Hutchinson et al. 2016, Miller et al. 2016, Schweitzer and Dey 2017) and that was first proposed by Leffelman and Hawley (1925) and Korstian (1927).

In an example of the benefit of maintaining a long-term study, once again the rehabilitation study of the 1940s (Jemison 1946), revisited in the 1950s (Wahlenberg 1953, Wahlenberg 1956), was used by Gene McGee (1967) to describe alternatives to clearcutting. He presented data that showed that partial harvesting did enable oak regeneration, and that a heavy cut followed by residual removal may be appropriate. Semantics notwithstanding, this described the shelterwood prescription of stages of disturbance that alter light to recruit then release oak. McGee (1972, p. 702) detailed the clearcutting results from this study in a similar manner as Roach (1968), in a paper "From a Defective Hardwood Stand to Multiple Use Opportunity', in which he states "Today the clearcut area is a pleasant place to visit."

At this point, there was solid research on the management of oak. It was well established that site productivity played a major role in determining successful oak establishment and recruitment, with oak reproduction readily attained on lower-quality sites and more challenging to obtain on higher-quality sites. Quantity was important, because oak reproduction had to be in adequate numbers to persist through a disturbance, whether the source was seedlings or sprouts. Sprouting from cut trees was more reliable for smaller-diameter trees than for larger-diameter trees. On good sites, new oak seedlings failed to compete with other faster-growing species, and several cultural practices were suggested to maintain oak. Controlling light levels in the understory was deemed the primary driver to successfully regenerating oak. The shelterwood method was advocated as the silviculture prescription in which the first disturbance allowed the small oak to grow into more competitive positions prior to overstory removal. Finally, many studies showed that single tree selection, or partial harvesting, did not sustain oak on good sites, and perpetuated tolerant species such as maple and beech. A final part of the oak regeneration puzzle was provided by Ivan Sanders, whose work showed that advanced oak reproduction needed to be 4.5 feet tall to be competitive once released (Sander 1972). The use of a partial harvest or shelterwood was suggested to get the small oak into this size class.

There was an explosion of conferences, symposia, and proceedings dealing with issues associated with oak-stand management. Three of these, Holt and Fischer (1979), Loftis and McGee (1993), and Spetich (2004), show a progression from examining basic management questions to addressing broader ecosystem-level functions. Loftis and McGee (1993, p. 319) summarized their symposium as ". . . scientists will provide answers to biological questions so that it is likely that oak regeneration in the future will be limited by economic and social constraints." But the question remains: Can we write a prescription to successfully regenerate oak on productive upland hardwood sites? A current conundrum exists over the use of fire as a silvicultural tool in upland hardwood forests with regard to successfully regenerating oak (Arthur et al. 2012, Hutchinson et al. 2012, Brose et al. 2013, Schweitzer et al. 2016, Waldrop et al. 2016, Iverson et al. 2017, Keyser et al. 2017). Frothingham (1917, pp. 12–13) stated ". . . (fire) is hardly to be recommended until experiments have thoroughly demonstrated its superiority to clear-cutting and girdling without burning." Research on fire in hardwood systems in the South has exponentially increased, but the short-term nature of these studies prevents accurate prediction as to the use of fire as a tool to obtain desired future conditions. As with the early reports on fire-damaged trees, apprehension exists over residual tree quality and wood quality following multiple fires and throughout long rotations (Reeves and Stringer 2011, Marschall et al. 2014, Wiedenbeck and Schuler 2014, Dey and Schweitzer 2015). Can we write a prescription to use fire in hardwood systems that will favor oak regeneration over other species without causing degrade to the residual stand? Or is it time to embark on a change in species dominance away from oaks? The American Hardwood Export Council actively advocates for American hardwood tree exports, and they have been successful in opening up foreign markets, especially China. They have re-branded yellow poplar as tulipwood, so that the international market does not associate it with the true poplars (*Populus*) and its associated wood properties. Early southern upland hardwood research focused on yellow poplar (see Keyser 2012), and in many disturbed stands, yellow-poplar regeneration is a nemesis to the oaks. What role can silviculture research play?

Hardwood silvicultural research must be held in good provenance. A chronology of ownership and methodology, documented in sufficient detail that it can be remeasured over long time periods, is paramount for long-term studies (>50 years), as demonstrated by projects reported by Schuler et al. (2016) and Knapp et al. (2017). The importance of such research, and changes and challenges in funding, has been detailed (see Wheeler et al. 2015, Olson and Saunders 2017). We should take care to build upon past efforts, including implementation and research results, and strongly advocate these projects as platforms to address today's questions and those that will be posed in the future.

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