EXPANDING THE SILVAH DECISION SUPPORT SYSTEM TO BE APPLICABLE TO THE MIXED-OAK FORESTS OF THE MID-ATLANTIC REGION

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Insights for Managers

Using SILVAH correctly to manage mixed-oak forests requires thoroughness and attention to detail. Key recommendations for its correct use include:

- **Conduct a complete inventory of the stand. SILVAH uses data collected from the overstory and understory strata to arrive at a recommended prescription. Incomplete or inaccurate inventory data will either cause SILVAH to not run or produce poor results.**
- **Pay attention to default settings. Ensuring the default settings are correct is as important as a quality inventory. These settings appear as user-defined choices such as desired forest type, favoring oak, starting a regeneration sequence, and wanting residuals post-harvest. Don't accept the default settings without question; rather, examine them in the context of the stand's conditions and your intentions for that stand.**
- **Obey the two "laws" of oak silviculture (Loftis 2004): To successfully regenerate mixed-oak stands, there must be adequate sources of competitive oak advanced reproduction and an adequate, timely release. Sander (1972) defined a competitive oak as being ≥4.5 feet tall; recent research is verifying that size (Brose et al. in press), so there must be an adequate density of oak stems 4-5 feet tall before the final harvest to meet future oak stocking objectives. Those oak stems must be exposed to at least 80 percent full sunlight via a final harvest to grow vigorously and successfully compete against the reproduction of other tree species (Miller et al. 2006).**
- **Remember young oak stands (ages 1-15 years). These stands need to be checked at least twice (Brose et al. 2008). Check them at age 3-5 years to determine if a competition problem is developing and take any necessary remedial action. Check them again at age 10-15 years to determine whether crop tree management is warranted to keep the dominant and codominant oak saplings in those canopy positions.**

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INTRODUCTION

In late 1999, the Pennsylvania Bureau of Forestry entered into a partnership with the USDA Forest Service's Northern Research Station to revise the SILVAH decision support system so that it would be more applicable to mixed-oak (*Quercus* spp.) forests. To expedite the revisions, the two agencies organized a committee of scientists and experienced field foresters who used relevant research results from other regions to devise interim inventory criteria and prescriptions. This approach accelerated the development process and facilitated acceptance of the interim guidelines in just a few years. This chapter describes in detail the work of that committee as well as science delivery efforts since the early 2000s that have resulted in an improved version of SILVAH that is applicable to mixed-oak forests and has been adopted entirely or in part in by several states in or bordering the mid-Atlantic region.

SILVAH, originally an acronym for Silviculture of Allegheny Hardwoods, is a systematic approach to silvicultural prescription development based on inventory and analysis of stand data. SILVAH began in northwestern Pennsylvania in 1967 when forest managers organized a Society of American Foresters meeting to examine regeneration failures that were, in their opinion, too common (≈50 percent) in the local maturing second-growth Allegheny hardwood and northern hardwood forests. They invited Ben Roach, a research assistant director of the USDA Forest Service's Northeastern Forest Experiment Station, to attend and participate. Managers considered the relative importance of seed production, soil and site factors, competing and interfering vegetation, and browsing by white-tailed deer (*Odocoileus virginianus*) as possible causes of the failures. Shortly thereafter, Roach assigned David Marquis to the Irvine, PA, laboratory and helped him recruit scientists of various disciplines from around the region to explore the factors that were leading to regeneration failures. By 1976 the Irvine research laboratory had accumulated enough results that it joined with the local Pennsylvania State University extension forester, Sandy Cochran, to offer 1-day training sessions to share those results with practicing foresters. The foresters readily adopted the lab's findings and recommendations, and the 50 percent regeneration failure rate in Allegheny hardwoods shrank to 10 percent in just a few years.

While SILVAH was being readily accepted and successfully used in the Allegheny and northern hardwood forest types, it offered little guidance in the expansive mixed-oak (*Quercus* spp.) forests and was not widely used by foresters working in that forest type. When the Pennsylvania Bureau of Forestry (PBF) sought third-party certification from the Forest Stewardship Council (FSC) in the late 1990s, FSC commended the structured framework of SILVAH and its success in regenerating Allegheny and northern hardwood forests and recommended its expansion to mixed-oak forests. The objective of this chapter is to tell the story of that expansion: how it occurred, the organizations and people involved, the obstacles encountered, how they were overcome, and the current status of the oak module of the SILVAH decision support system.

OAK REGENERATION STOCKING CRITERIA

In January 2000, Gary Rutherford, the PBF silviculture section chief, convened a committee of scientists and managers to develop a plan to implement the FSC recommendation. The committee included scientists from Forest Service research labs at Irvine, PA, and Morgantown, WV; faculty from Pennsylvania State University; and experienced field foresters from the Allegheny National Forest, PBF, and forest industry. The initial meeting focused on determining which species and species groups to add to SILVAH, what constituted a stocked plot for those additions, and how their stocking criteria should vary by deer impact and site quality. SILVAH uses the stocked plot concept to combine the key regeneration attributes of seedling density and seedling height. A stocked plot is defined as a regeneration inventory plot

Table 1.—Initial changes made by the SILVAH revision committee in 2000 to the size and regeneration plot stocking criteria of oak seedlings. The three-number sequence for the competitive oak seedling category represent the low, medium, and high site classes of the Pennsylvania Bureau of Forestry. The asterisks (*) denote weighted stem counts as oak seedlings more than 1 foot tall were counted twice.

		Deer Impact Level (Marquis and others 1992)				
Seedling Category	Height (feet)	1	2	3	4	5
				Before 2000		
Small oak	0.2 to 4.5	10*	20*	30*	40*	60*
Large oak	>4.5	1	1	1	1	1
				After 2000		
New oak	<0.5	25	25	50	100	200
Estblished oak	0.5 to 3.0	12	12	25	50	100
Competitive oak	>3.0	1, 2, or 3	1, 2, or 3	1, 2, or 3	1, 2, or 3	1, 2, or 3

that contains enough seedlings of a given species and size that one of those seedlings will likely occupy that plot in the next stand after a final harvest. SILVAH uses the proportion of stocked plots in a stand as a major factor to develop the recommended silvicultural prescription.

SILVAH 5.0, the version in use in 2000, categorized oak seedlings as large or small (Table 1; Marquis et al. 1992). Large oak seedlings were >4.5 feet tall and small oak seedlings were <4.5 feet tall. Stocking criteria for these two sizes of oak seedlings were one large oak and 10-60 small oaks per plot, depending on the deer impact. Because these criteria were virtually never found in oak stands, SILVAH would recommend defer cut. In the rare instances that oak stands had 70 percent of their regeneration plots stocked with adequate numbers of large or small oak, SILVAH would recommend a clearcut—complete overstory removal. The committee felt that the height and plot stocking criteria were incorrect, overlooked the root-centric growth strategy of oak seedlings (Brose 2011a), and ignored the influence of site quality (Minckler and Woerheide 1965, Trimble 1973). Additionally, the two most common oak prescriptions—defer cut and clearcut—were single-treatment prescriptions and did not include the sequencing of multiple oak regeneration practices such as the shelterwood-burn technique or the herbicide shelterwood method that had been recently developed (Brose et al. 1999, Loftis 1990a).

Because of programming limitations in SILVAH at the time (code was written in Fortran 77 and used a DOS interface), the committee considered all oak seedlings and sprouts together as "oak" regardless of species. They also created three groups of oak reproduction—competitive, established, and new—based on height or root collar diameter (RCD). Competitive oak were >3 feet tall or had RCDs >0.75 inch. These were considered large enough to dominate a regeneration plot by crown closure of a new stand (approximately 10-15 years post-harvest). Established oak were 0.5-3 feet tall or had RCDs of 0.25-0.75 inch. Oak reproduction of this size class was considered large enough to survive silvicultural operations, including growing-season prescribed fire, and sprout afterward. They were also considered to be competitive on low-quality sites (oak site $index_{50}$ <65 feet). New oak were <0.5 feet tall or had RCDs <0.25 inch. Reproduction of this size could not sprout after a growing-season prescribed fire or other intense silvicultural operations. Oak seedlings of this size need favorable growing conditions and ample time to grow into established seedlings.

To determine the stocking criteria for competitive, established, and new oak, the committee had to define a mature oak forest. To do this, the committee used overstory inventory data collected from 54 mature undisturbed oak stands scattered across Pennsylvania, West Virginia, and southern Ohio to determine the average attributes of an oak stand. The data showed that

Table 2.—Dominance probabilities at age 20* for oak seedlings by site index for southern Missouri (MO) and western North Carolina (NC). The Missouri probabilities are averages calculated across all aspects from Sander and others (1984) while the NC probabilities are taken directly from Loftis (1990).

Basal (inches)	Oak Site Index (height in feet at age 50)					
	50(MO)	60(MO)	70(MO)	70(NC)	80(NC)	90(NC)
0.1				0.01	0.00	0.00
0.2	0.01	0.01	0.00	0.02	0.01	0.00
0.3				0.04	0.02	0.01
0.4				0.06	0.03	0.01
0.5	0.16	0.15	0.03	0.09	0.04	0.02
0.6				0.13	0.06	0.03
0.7				0.17	0.09	0.04
0.8				0.21	0.12	0.06
0.9				0.25	0.15	0.08
1.0	0.41	0.37	0.12	0.29	0.18	0.11
1.1 to 1.5	0.58	0.50	0.19	0.38	0.29	0.19
1.6 to 2.0	0.68	0.73	0.28	0.46	0.41	0.34

* The likelihood that a seedling of a given basal diameter at the time of overstory removal will grow to be in a dominant or codominant crown position when the next stand is 20 years old.

the average oak stand was 80 years old, had 250 trees per acre, 120 square feet of basal area, and 100 percent stocking. Of the 250 trees, only 60 were in the main canopy (dominants or codominants), and 43 were oak. These 43 oaks accounted for 56 percent of stand stocking. These two numbers—43 mature oak per acre and 56 percent stocking—represented the desired future condition, i.e., the primary components of the new "oak stand" created by a regeneration prescription.

With the goal identified (43 mature oaks per acre and 56 percent oak stocking at age 80), the committee used 3 long-term studies (Loftis 1990b, Sander et al. 1984, Ward and Stephens 1994) to determine how many oak seedlings were needed on a 6-foot radius regeneration plot at the time of the final harvest (age 0 years) to constitute a stocked plot. Ward and Stephens (1994) reported the crown position retention rates for northern red oak (*Quercus rubra*) from age 25 to 85 in mixed hardwood stands in Connecticut. They showed that 30-35 percent of the dominant and codominant oaks at age 25 would still be in those crown positions at age 85. The others would either slip to intermediate or suppressed canopy positions or die. Also, they showed that only 5 percent of the intermediate or suppressed northern red oaks at age 25 would move up to dominant or codominant canopy positions by age 85. The committee used these findings to calculate that 135 dominant or codominant oak saplings were needed at age 25 to produce 43 dominant or codominant oak trees at age 85 ($(43/0.32) \times 100 \approx 135$).

The committee used dominance probability studies conducted in Missouri and North Carolina to calculate how many oak seedlings per acre were needed at age 0 to produce 135 dominant or codominant oak saplings at age 25 (Loftis 1990b, Sander et al. 1984). Both studies followed the performance of oak reproduction for 5-8 years after the final harvest and then conservatively projected their likely crown positions at age 20. These projections, or dominance probabilities, reflected the influences of initial size of the oak reproduction and site quality (Table 2). Depending on these two factors, the committee calculated that 380-13,500 oak seedlings or sprouts per acre were needed at the time of the final harvest to produce 135 oak saplings at age 20. This range of oak seedlings and sprouts translated to 1-35 oak stems per 6-foot radius regeneration plot, depending on initial seedling size and site quality.

One factor lacking from the Missouri and North Carolina studies was the influence of excessive white-tail deer browsing of oak reproduction because herbivory was not a serious problem at either location. In Pennsylvania, deer browsing was a major obstacle to regenerating forests (Horsley et al. 2003; Marquis 1974, 1975; Marquis and Grisez 1978; Marquis and Brenneman 1981) and had to be considered in the seedling stocking criteria. For new oak, the committee decided that a minimum of 25 seedlings per plot was needed at deer impact levels 1 and 2 and 50, 100, and 200 seedlings per plot at deer impact levels 3, 4, and 5 (Table 1). Minimum seedling counts for established oak were half those of new oak; 12-100 stems per plot depending on the deer impact level. Competitive oak stocking was set at one stem per plot regardless of the deer impact level, because deer browsing damage is diminished for taller seedlings. However, competitive oak stocking did vary from 1-3 stems per plot by site quality, because mesophytic hardwood reproduction would become more problematic as site quality improved (Carvell and Tryon 1961, Crow 1988, Minckler and Woerheide 1965, Trimble 1973).

By 2000, harvested oaks were proven to produce highly competitive stump sprouts to varying degrees depending on the species and the diameter of the parent tree (Johnson et al. 2009). The probable contribution of oak stump sprouts to regeneration stocking was already in the pre-2000 versions of SILVAH (Marquis et al. 1992). Therefore, the committee opted to keep these probabilities as they were for deer impact levels 1 and 2 but decreased them by 50 percent for deer impact level 3 and discounted them completely for deer impact levels 4 and 5.

OAK REGENERATION PRESCRIPTIONS

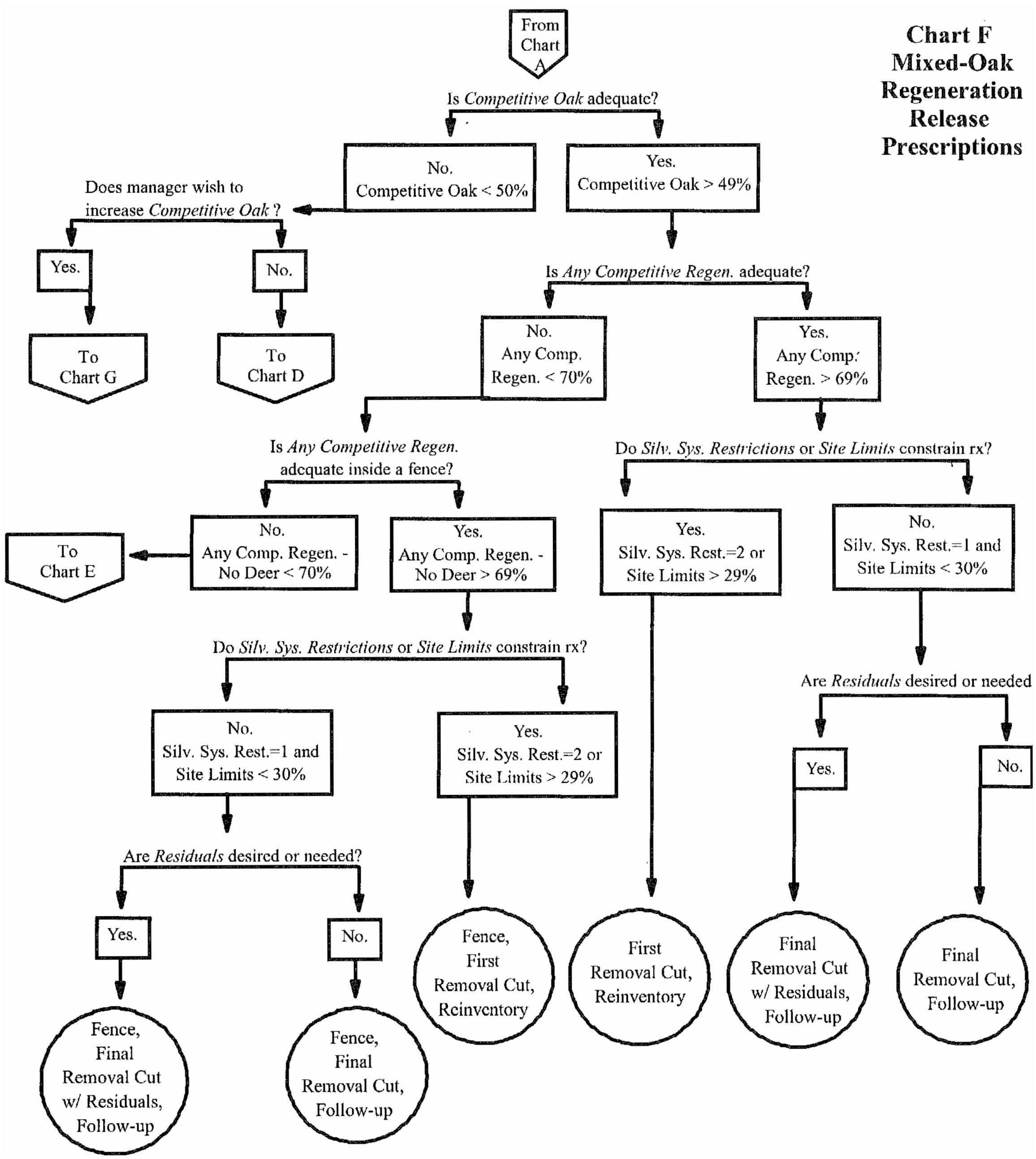
Once the committee had determined stocking criteria for oak reproduction, the next task was to review and revise the SILVAH prescriptions for their appropriateness in regenerating mixed-oak forests. At the time there were no oak-specific prescriptions; oak reproduction was treated the same as all other desirable seedlings. Because of this lack of differentiation between oak reproduction and that of other desirable species, pre-2000 SILVAH prescriptions tended to convert mixed-oak forests to Allegheny hardwood or other forest types. The committee members found this tendency to be unacceptable, so they began formulating new prescriptions designed around the silvics of oak and the oak regeneration process.

From the outset of this endeavor, the committee recognized that several intrinsic and extrinsic factors extended the longevity of the oak regeneration process, which could take 5-25 years. At the forefront of the intrinsic factors were the sporadic occurrence of acorn crops (masting) in the mid-Atlantic region and the root-centric growth pattern of oak seedlings (Brose 2011a, b). Masting of mature oaks tends to be periodic because of the physiological strain of producing large seeds. When there is an acorn crop, the resultant new seedlings emphasize root growth in lieu of stem development until the seedlings have a large enough root system to support sustained vigorous height growth (Brose 2011a). Both factors slow the oak regeneration process, and both can be adversely affected by numerous environmental factors (Loftis and McGee 1993). Consequently, an already slow regeneration process can be made even slower. For example:

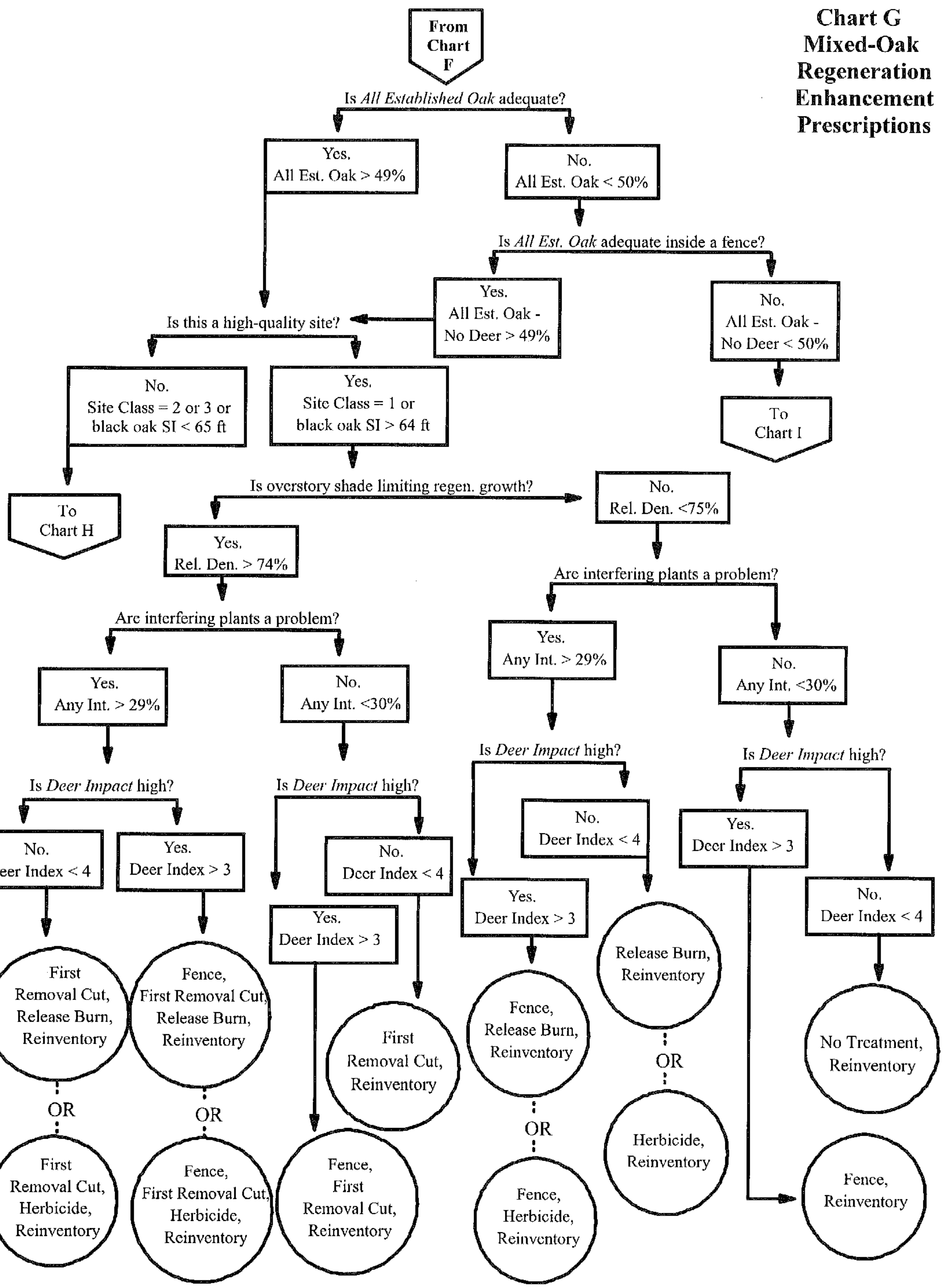
- Wet spring weather can result in poor pollination.
- A late frost can kill oak inflorescence.
- Summer droughts or defoliations can cause oaks to abort nascent acorn crops.
- Dense understory shade and deer browsing can prevent young oak seedlings from developing larger, more competitive root systems.

To account for the slow, punctuated nature of the oak regeneration process, the committee devised six decision charts (F to K) around common situations often found in the mid-Atlantic region (Fig. 1):

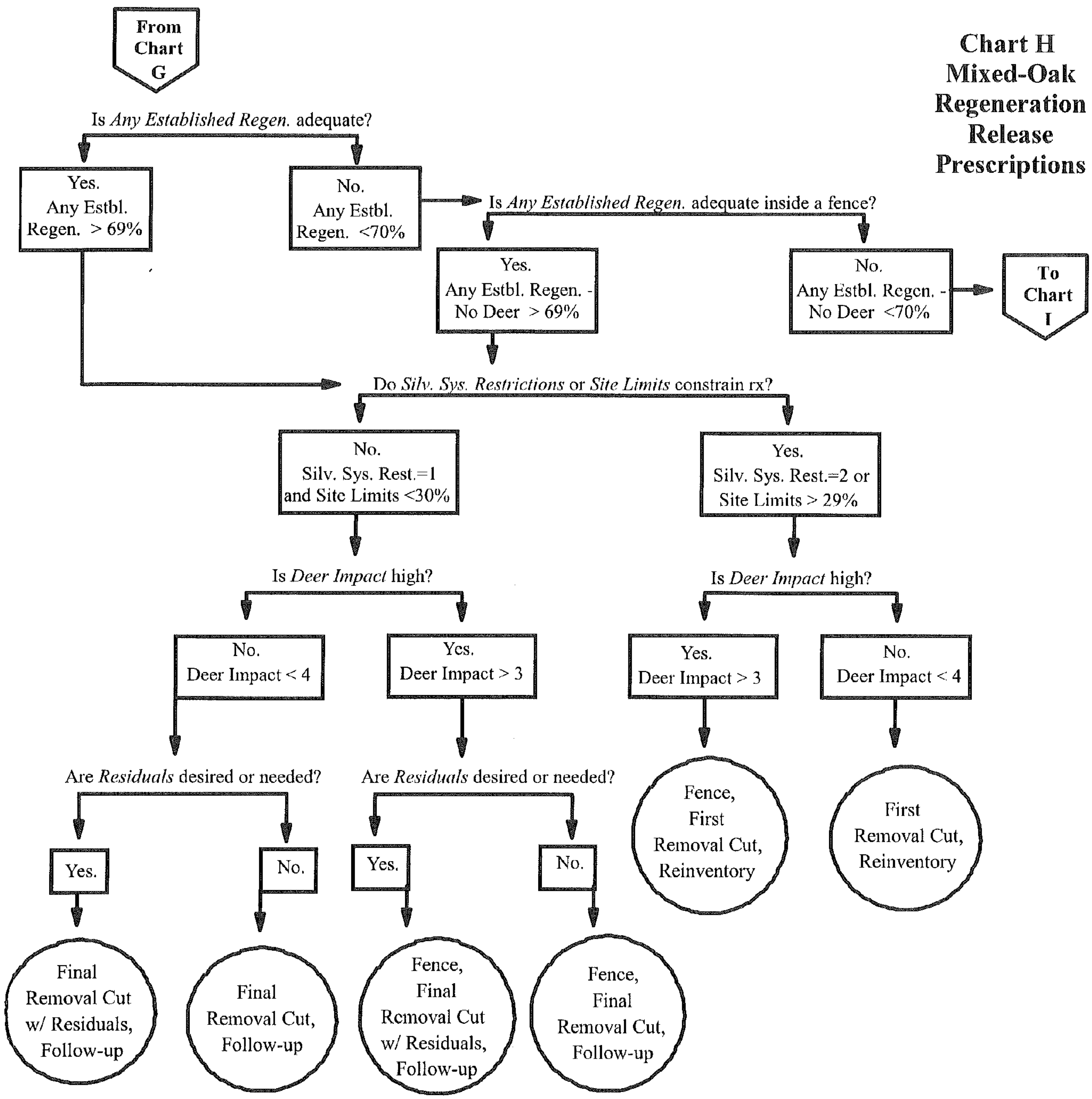
- Chart F: Competitive oak reproduction is adequate and ready for release. This chart is for oak stands nearing the end of the oak regeneration process. Such stands have an adequate stocking (≥50 percent) of competitive oak seedlings, ≥70 percent total competitive regeneration, and an overstory suitable for an economical final harvest. Of the six prescriptions, four were final removal cuts with deer fencing and retention of long-term residual trees as needed. The other two prescriptions were shelterwood first removal cuts, which were made for aesthetic or edaphic reasons.



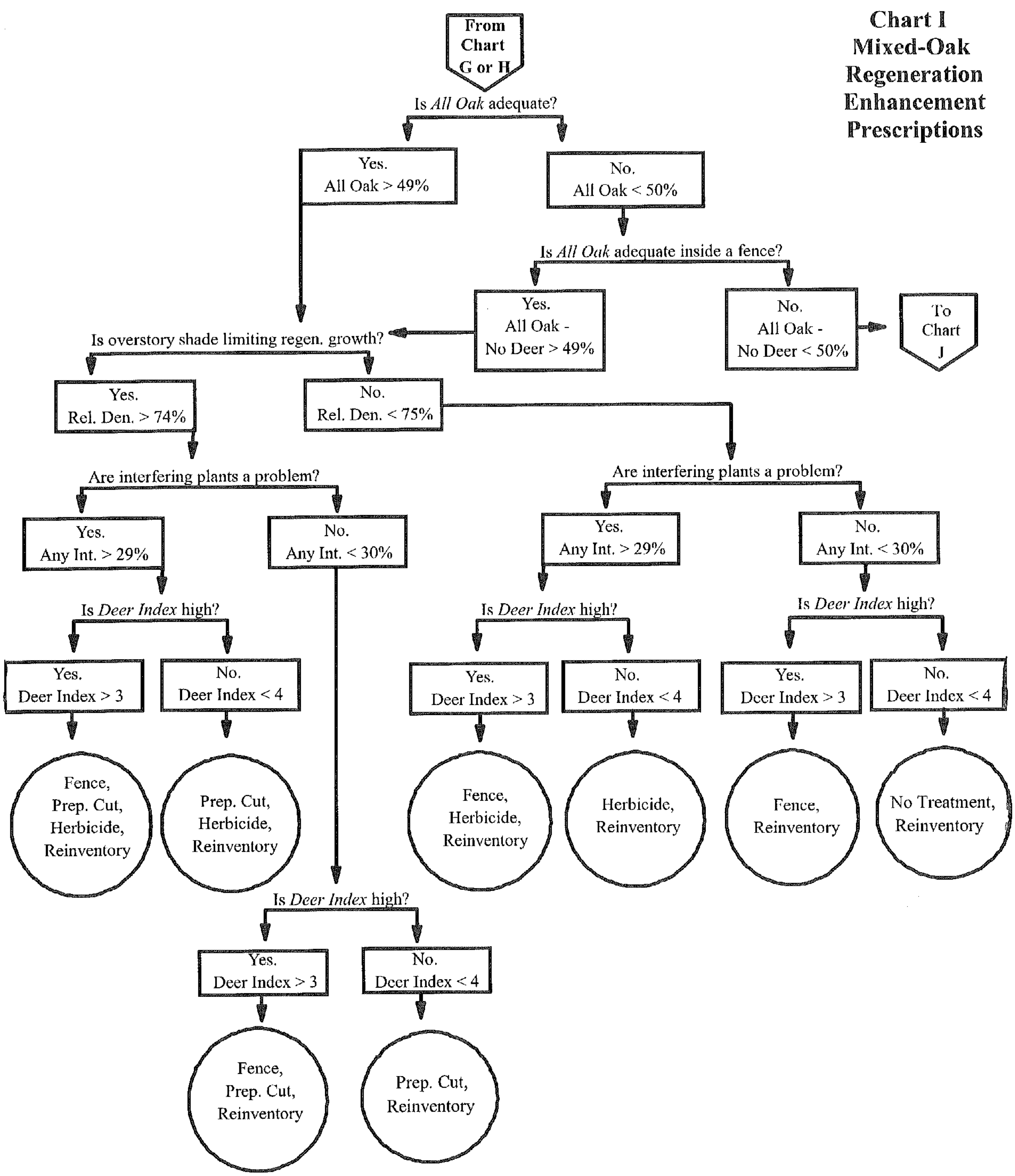
- Chart G: Established oak seedlings are adequate and ready for development into competitive reproduction. This chart addresses oak stands on high-quality sites (oak SI_{50} ≥70 feet) that are in the middle of the oak regeneration process and should be ready for a final harvest in 5 to 10 years if properly managed. These stands have at least 50 percent stocking of established oak seedlings, but these seedlings are not yet large enough for a final harvest due to fierce competition from other tree species. Also, one or more barriers (overstory shade, interfering vegetation, deer) hinder the development of those seedlings. A first removal cut of a two-cut shelterwood sequence is recommended to decrease shading, and either herbicide application or release burning is advised to combat interfering vegetation. Woven wire fencing is suggested to alleviate deer browsing. At the end of each prescription a reinventory is necessary to determine whether the stand is ready for the next sequence of treatments or Chart F.



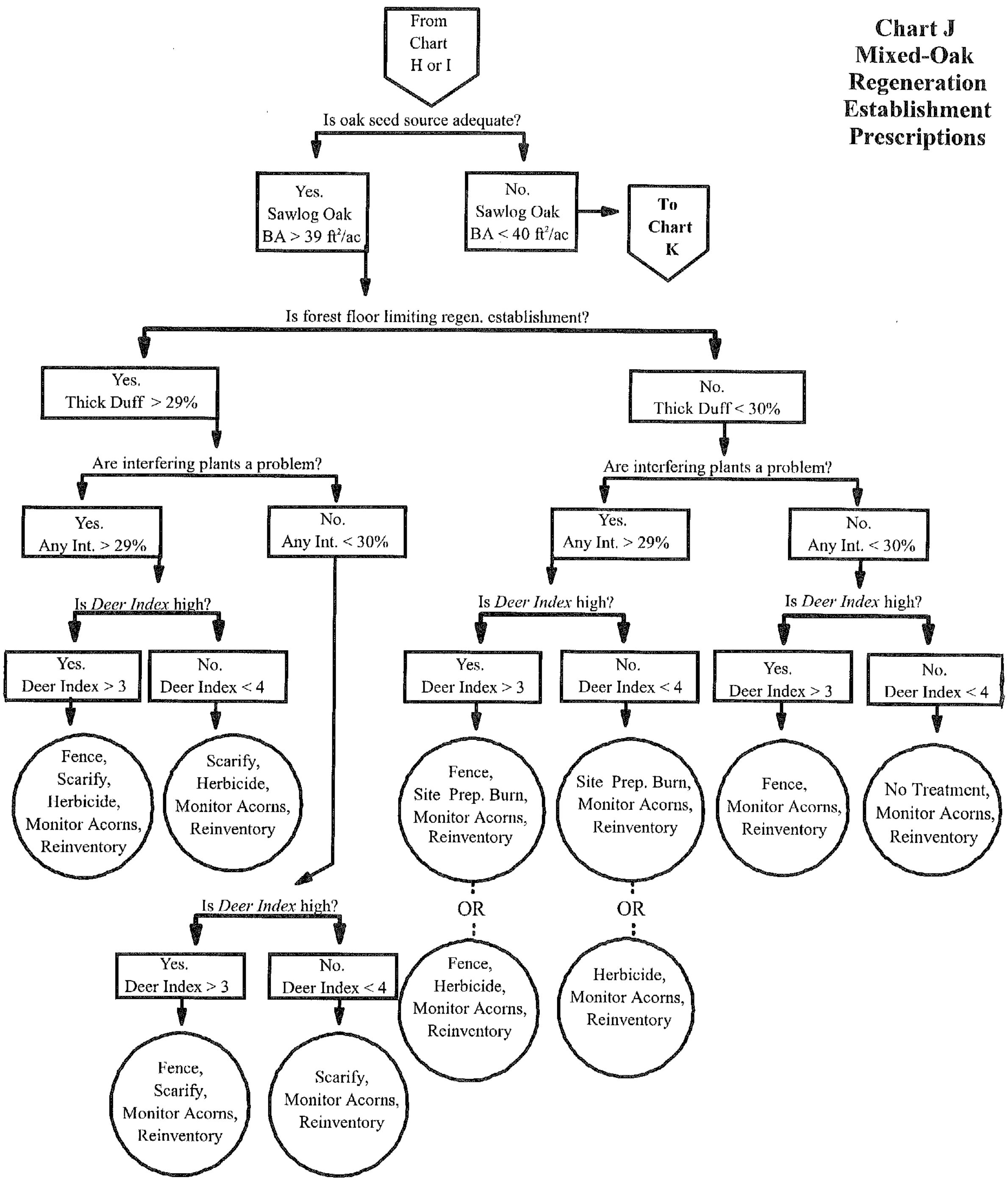
- Chart H: Established oak seedlings are adequate and ready for release. Chart H is for oak stands on low-quality sites (oak SI_{50} <65 feet) that have >50 percent stocking of established oak. Such stands are near the end of the oak regeneration process, because interfering vegetation is much less problematic; thus, small oak seedlings can be competitive (Johnson et al. 2009). Chart H prescriptions are nearly identical to those in Chart F, in that both recommend either final or first removal harvests. Deer fencing may also be recommended if post-harvest browsing is adversely affecting the oak reproduction.



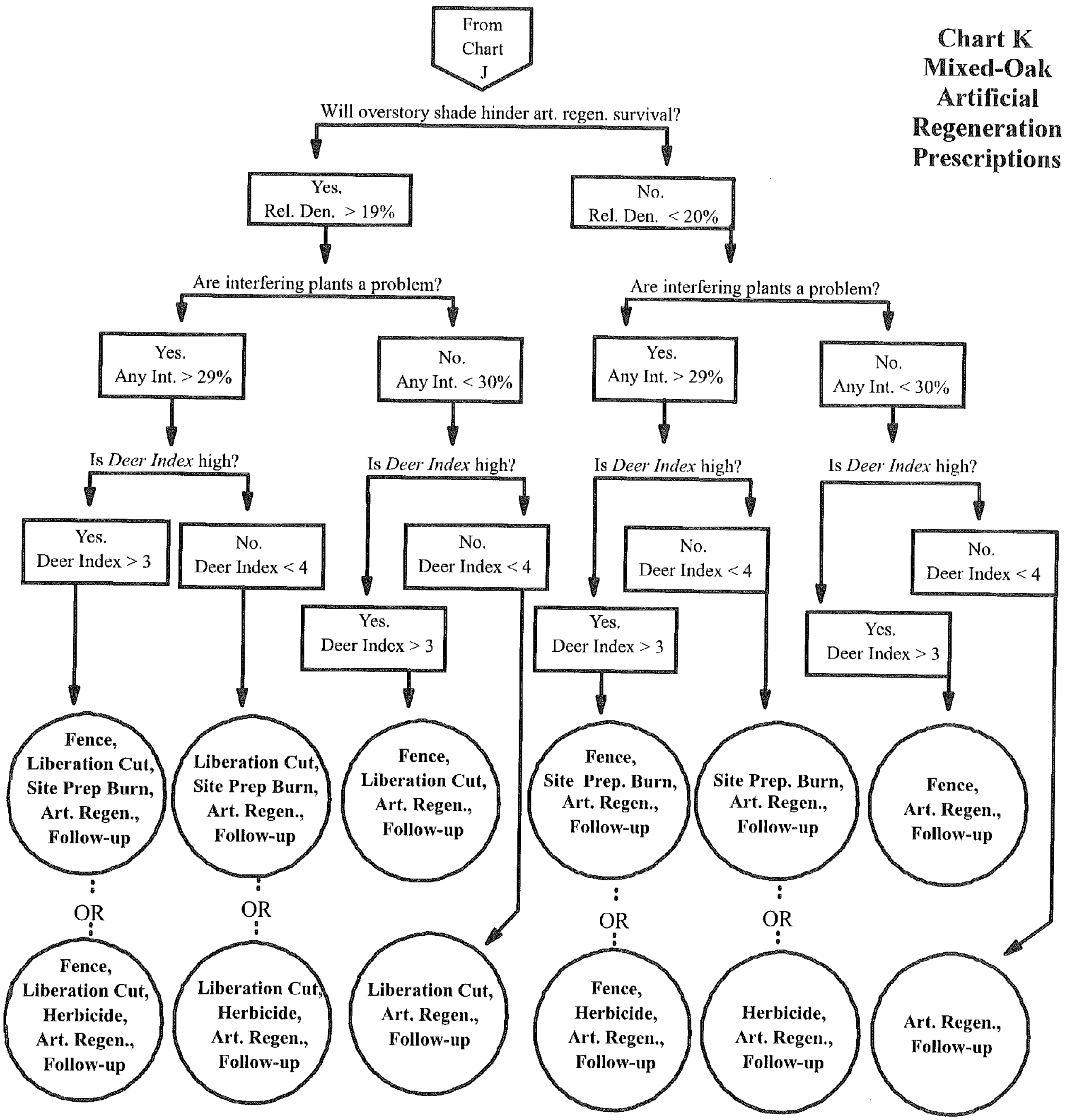
- Chart I: New oak seedlings are adequate and ready for development into established reproduction. Chart I addresses oak stands that recently had a good to bumper acorn crop resulting in the formation of a cohort of new oak seedlings that exceeds 50 percent stocking. Such stands are at the very beginning of the oak regeneration process and are many years from completion. The prescriptions are designed to foster the root development of the new oak seedlings while minimizing their mortality. This is done by gently increasing understory lighting via the preparatory cut of a three-cut shelterwood sequence and the use of individual stem herbicides. Fire is not a Chart I prescription, because the new oaks are too small to withstand burning (Miller et al. 2017). Fencing is advised if deer browsing is problematic and a subsequent inventory is necessary to determine when the stand is ready to proceed to Chart F, G, or H.



- Chart J: New oak seedlings are lacking, but an adequate seed source is present. This chart is for oak stands that do not have enough oak reproduction of any type (<50 percent cumulative stocking) to start the oak regeneration process. Such stands are between bumper acorn crops; the oak seedling cohort established after the last major masting event has died out and the next one is sometime in the future. These stands have an adequate acorn source (≥40-square-foot basal area of sawlog-size oaks) and may have interfering vegetation or root mat problems in the understory. The eight prescriptions include herbicide application, seedbed preparation burning, and soil scarification, which mitigate obstacles to establishing new oak seedlings coupled with monitoring for future acorn crops. A follow-up inventory is recommended to determine when these stands are ready to move onto the prescriptions of the preceding charts.



- Chart K: New oak seedlings and an adequate seed source are lacking. This chart is for oak stands that have been degraded by past disturbances such as insect defoliations, storm damage, or exploitative harvesting, which result in excessive removal of oak seed sources. These stands have lost enough of their overstory oaks to have insufficient seed source to establish new oak seedlings. The eight prescriptions recommend intensive site preparation treatments followed by relatively expensive artificial regeneration to compensate for the lack of seed source.



Within each of these possible starting points for practicing foresters, the committee developed 6 to 12 oak regeneration prescriptions. These prescriptions centered on even-age management, specifically the shelterwood system. Uneven-age silviculture was not considered; it had a long history of failure in the mid-Atlantic region because of chronic deer overpopulations and the chance it would devolve into diameter-limit cutting. This would result in undesirable changes in species composition. Generally, the oak regeneration prescriptions consisted of multiple treatments applied sequentially over several years. They included practices already used in the mid-Atlantic region; i.e., broadcast herbicide application and deer fencing, and ones successfully used in other regions such as midstory shade removal and prescribed burning (Brose et al. 1999, Loftis 1990a). The prescriptions also included subsequent inventories to ensure conditions were correct for the next treatment.

SCIENCE DELIVERY

Once the committee tentatively identified new oak stocking criteria and formulated draft prescriptions, they needed to be field tested and shared with practicing foresters. This dissemination served two purposes: it addressed the dearth of scientific management of mixed-oak forests in the region, and it facilitated partnered testing of the inventory criteria and prescriptions. The Forest Service scientists taught the new criteria for determining stocking of oak reproduction to approximately 100 PBF field foresters in early summer 2000. These foresters used the new criteria in their understory inventories for the next 16 months and then provided feedback to the committee on their applicability and ease of use. Generally, the foresters accepted the new criteria, but the committee made a few minor changes based on their recommendations. For example, established oak and competitive oak were combined for stands with an oak site index <70 feet at age 50 years.

Commencing in 2002, Forest Service scientists disseminated the interim inventory guidelines and the draft prescriptions via annual training sessions held at Clear Creek State Forest near Brookville, PA. Additional workshops were provided in Kentucky, Maryland, Ohio, and West Virginia, where participants provided feedback based on local experiences. To date, more than 800 of these forest managers have attended the training sessions held at Clear Creek State Forest or one of the periodic sessions held in neighboring states. The oak training session is mandatory for all new foresters hired by the PBF as well as the Pennsylvania Game Commission and the Allegheny National Forest.

By 2007, revisions to the inventory criteria and prescriptions based on feedback from the PBF foresters had largely ceased. Therefore, the Forest Service scientists published a SILVAH–oak regeneration guidebook (Brose et al. 2008). Since this guidebook was published, more than 2000 copies of the have been distributed to forest managers throughout the eastern United States.

SUBSEQUENT RESEARCH

Expanding SILVAH to mixed-oak forests highlighted several knowledge gaps in regional oak ecology and silviculture. The principal scientists of the SILVAH–oak endeavor have been able to address many of these gaps thanks to continued financial support by the PBF and funding from other sources, such as the Forest Service and the Joint Fire Science Program. Research studies that have been conducted or are ongoing include:

1. The Acorn Study. This project followed the survival of the 2001 bumper acorn crop and subsequent oak seedling cohort for 8 years (Brose 2011b). Principal findings were:
   a. Soil scarification is valuable in protecting acorns from insects, diseases, weather, and wildlife consumption.

   b. Deer browsing and dense understory shade were reaffirmed as the two most detrimental obstacles to oak seedlings.

2. The Dominance Probability Study. This large-scale, long-term project documents the post-harvest performance of oak seedlings and sprouts across a wide variety of oak site indices throughout Pennsylvania (Brose et al. in press). Currently in its 15th year, it will produce oak dominance probabilities that will replace the interim ones derived from the Missouri and North Carolina studies.
3. The Limiting Factors Study. Another long-term study that follows the survival and growth of oak seedlings from the 2001 acorn crop (Miller et al. 2017). A major finding was that multi-treatment prescriptions are needed to control interfering ferns and competing non-oak reproduction, deer browsing, and understory shade.
4. The Mountain Laurel Study. This project identified the level of cover at which mountain laurel starts interfering with oak seedlings and the strengths and weaknesses of several possible control strategies (Brose 2016, 2017). It also spawned a follow-up study to identify potential broadcast herbicide prescriptions (Brose and Miller 2019, Miller et al. 2016).
5. The Oak Rooting Study. This project examined the development of the roots of oak seedlings growing in the understory light conditions created by a three-cut shelterwood prescription (Brose 2011a, Brose and Rebbeck 2017). Key findings were:
   a. Northern red oak can develop roots in preparatory-cut stands.
   b. First removal cuts must create and maintain at least 30 percent sunlight for all oak species.
   c. Root development must continue for at least 6 years before oak seedlings switch to emphasize height growth.
6. The Prep Cut Study. This project focused on the survival and development of northern red oak seedlings subjected to three levels of understory lighting, all of which could be achieved via a shelterwood prep cut treatment (Miller et al. 2014). A major finding was that removing non-oaks <3-inch diameter at breast height was optimal; removing fewer did little to promote oak seedling survival and growth, and removing more sparked competition from black birch.
7. SILVAH Success Study. This ongoing project tests the SILVAH-generated prescriptions applied by PBF foresters in the early to mid-2000s (Rittenhouse et al. 2018).

CONCLUSIONS

Expanding SILVAH to be more applicable to the mixed-oak forests of the mid-Atlantic region has been a 17-year journey of collaboration and cooperation between Forest Service scientists and a broad array of other forestry professionals. By using relevant oak research from other states, the committee could quickly produce tentative guidelines for inventorying oak seedlings and determining stocking criteria to formulate draft prescriptions. Field testing and feedback from numerous foresters have helped hone those criteria, guidelines, and prescriptions to the environmental conditions of Pennsylvania's forests and has sped acceptance as the practitioners have developed a sense of ownership in the developmental process. Moreover, practicing foresters have begun to see positive results in regenerating oak forests from their own application of SILVAH. These cooperative relationships will endure, thereby keeping SILVAH current and useful to future managers of mixed-oak forests in the mid-Atlantic region.

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