

CENTERPIECE OF RESEARCH ON THE PENOBSCOT EXPERIMENTAL FOREST: THE U.S. FOREST SERVICE LONG-TERM SILVICULTURAL STUDY

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Abstract.—Established between 1952 and 1957, the U.S. Department of Agriculture, Forest Service experiment comparing several silvicultural treatments is not only the centerpiece of research on the Penobscot Experimental Forest in Maine, it is also one of the longest-running, replicated studies of how management techniques influence forest dynamics in North America. Ten treatments representing even- and uneven-aged silvicultural systems and exploitative cutting are replicated twice on operational-scale experimental units averaging 21 acres in size. Treatments are applied uniformly to experimental units in accordance with prescriptions designed to direct both stand structure and composition. In some treatments harvests are scheduled at intervals (e.g., 5, 10, or 20 years); in others, harvests are triggered by stand conditions. Each experimental unit, or compartment (most recently termed management unit), has an average of 18 permanent sample plots (PSPs) for measuring attributes of trees ≥ 0.5 inches in diameter at breast height. Tree regeneration and other vegetation are measured on multiple subplots within each PSP. Measurements are taken before and after harvests and, in many treatments, at intervals between harvests. Over the past 60 years, this long-term experiment and associated short-term studies have generated fundamental knowledge about forest ecosystems and silvicultural guidelines for the northern conifer forest type, and, in a more general sense, have contributed to our understanding of mixed-species forest science and management.

INTRODUCTION

Between 1952 and 1957 the U.S. Department of Agriculture, Forest Service established a long-term silvicultural experiment on the Penobscot Experimental Forest (PEF) in Maine. It is currently titled *Silvicultural Effects on Composition, Structure, and Growth of Northern Conifers in the Acadian Forest Region: Revision of the Compartment Management Study on the Penobscot Experimental Forest*. This experiment was one of a series of similar studies on experimental forests across the United States. These experiments were called “compartment management studies” because they were designed around large, essentially operational-scale, experimental units (≈ 20 -40 acres) (metric conversions are in Appendix I) known as compartments. Very few of those studies were continued as planned, but

research has proceeded on the PEF with periodic harvests and regular re-measurement of treatment effects on tree and stand growth and other response variables.

A series of study plans has guided the long-term silvicultural experiment on the PEF. The most recent plan, by J.C. Brissette and L.S. Kenefic, was approved January 2008 and was an update and revision of one submitted by R.M. Frank, Jr. and approved in May 1975. Frank’s study plan superseded the original plan of January 1953 by T.F. McLintock and subsequent revision by A.C. Hart in June 1962. Each of the revisions updated the long-term study to adjust to changing research priorities, build on what had been learned thus far, and ensure the relevance of the experiment for future scientists and managers. Results

from the first 40 years of this study were summarized by Sendak et al. (2003). This paper focuses on the experiment as it is being carried out under the current study plan. Details about changes that have occurred over the years in treatment structure and response variables can be found in metadata associated with the measured data (Brisette et al. 2012).

Much has changed in the 60 years since this study was first conceived. Social and political ramifications of forest management have brought debate about appropriate silviculture into the public arena. Logging systems have advanced from hand felling and horse skidding to cut-to-length processors and forwarders. However, many of the fundamental issues that prompted installation of the study remain the same. Spruce budworm (*Choristoneura fumiferana*) is still a threat and discussions continue about the role of silviculture in reducing impacts during outbreaks. Diameter-limit harvesting is still practiced and its long-term effects debated. For social, economic, and biologic reasons, natural regeneration remains the predominant method of establishing new trees and stands in the northeastern United States, but many questions about ensuring adequate regeneration of desired species are yet unanswered. Because of the silvics of the major species in the northern conifer forest of which the PEF is representative—red spruce (*Picea rubens* Sarg.), balsam fir (*Abies balsamea* [L.] Mill), eastern white pine (*Pinus strobus* L.), eastern hemlock (*Tsuga canadensis* [L.] Carr), paper birch (*Betula papyrifera* Marsh), and red maple (*Acer rubrum* L.)—both even- and uneven-aged silvicultural systems can be used and no one system has achieved universal acceptance. Questions remain about the entire array of silvicultural options available to natural resource managers.

The long-term study on the PEF has experimental design limitations that cannot be corrected, the most serious being only two replicates of the treatments (see Frank and Kenefic, this volume) and separation of the control from the rest of the experiment (Kenefic et al. 2005b). However, the study is unique because of its longevity, integrity of the original treatment structure,

timeliness of treatment application, and the quality of the long-term database (Brisette et al. 2006; Kenefic et al. 2006; Russell et al., this volume). We feel that these qualities more than make up for the shortcoming in experimental design.

The primary objective of the study is to quantify tree and stand response to silvicultural treatment. Response variables are regeneration; species composition; and tree and stand growth, productivity, and quality. These data provide information about the interaction of natural and human disturbances and their effects on stand dynamics. To meet this objective, the hypotheses address some of the important unanswered questions about managing mixed northern conifer stands in the region. For example: Do responses vary between...

- ... managed and unmanaged stands?
- ... stands managed with clear silvicultural objectives and stands exploited for current timber production with no concern for future composition, structure, or condition?
- ... stands managed for one or two cohorts and stands managed for multiple cohorts?
- ... stands that once regenerated are left to develop naturally and stands that receive tending treatments such as cleaning or thinning?

Because of the range of response variables measured, this experiment not only answers questions about *whether* treatments differ but also addresses *how* treatments differ and *what* about them differs.

Defining hypotheses to test is an important part of study planning. But in a long-term experiment such as this one, the most enlightening outcomes cannot be planned for; that is, an important aspect of this experiment is studying the unpredicted and unexpected. Although the unexpected cannot be articulated in a hypothesis statement, it can be stated that this study addresses questions about the uncertainty inherent in any silvicultural treatment because of the long-term nature of stand development and the unpredictability of sporadic natural disturbance

events and the likely prolonged effects of climate change. In addition to understanding the various pathways of stand development initiated by particular silvicultural manipulations, managers need to know the likelihood of achieving their desired objectives along those pathways. Such knowledge is best attained through long-term monitoring, where understanding increases incrementally with every measurement cycle.

A secondary objective of this study is to provide a variety of forest structures at one location to be used as the framework for short-term experiments in ecology and silviculture (see Appendix II for some examples). The long-term experiment can best be described as empirical; the short-term studies are often process-oriented and thus can address *why* treatments differ.

Ultimately, results from this long-term experiment and associated short-term studies generate fundamental knowledge about forest ecosystems and science-based management guidelines for northern conifers and associated species in the Acadian Forest Region of Atlantic Canada and adjacent Maine. In a broader sense, results from this study influence forest science and management of shade-tolerant conifers globally.

To fully understand the design and significance of the experiment, it is important to put it into context regarding its location, the range of silvicultural alternatives represented in the treatment structure, and the silvics of the species under study.

Acadian Forest

The Acadian Forest contains a mixture of northern conifers and hardwoods dominated by spruces (*Picea* spp.) and balsam fir. Species composition is highly variable and influenced by both latitude and site, with a greater proportion of conifers on low-lying and more northerly areas. Halliday (1937) first described the Acadian Forest Region in a classification of Canada's forests. The Acadian Forest spans the provinces of New Brunswick, Nova Scotia, and Prince Edward Island, and in the United States, Maine and higher elevations of the Appalachian Mountains. The adjacent

and closely related Great Lakes-St. Lawrence Forest Region extends west through southern Quebec and Ontario (Rowe 1972). The Boreal Forest Region lies north of the Acadian and Great Lakes-St. Lawrence regions. Maine juts into eastern Canada, with New Brunswick to the east and north, and Quebec to the north and west. The Laurentian Mixed Forest Province, Warm Continental Division (McNab and Avers 1994) north of Portland, Maine, has been identified with the Acadian Forest (Braun 1950).

The PEF is located in the southern extent of the Acadian Forest Region, in the towns of Bradley and Eddington in east-central Maine (44°54' N, 68°38' W) (Fig. 1). The dominant conifers are shade-tolerant and regenerate well under canopy cover. Advance regeneration is prolific (Brissette 1996), and without it regenerated stands are converted to a hardwood composition (Hart 1963). Balsam fir and spruce species are the principal commercial softwoods. Though the amount and early growth rates of fir regeneration surpass those of spruce, fir longevity and maximum diameter are approximately half those of the spruce species. Fir is also the preferred host of the spruce budworm (see below). Furthermore, the ability of fir to extend its root system on better sites gives it

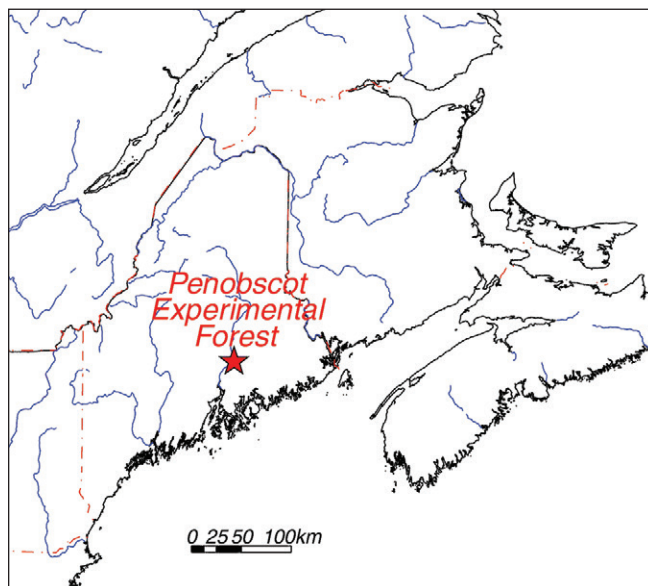


Figure 1.—Location of the Penobscot Experimental Forest in the northern conifer forest region.

an additional advantage over spruce, which has a more shallow rooting system (Blum et al. 1983, Tian and Ostrofsky 2007). Management of spruce-fir stands should utilize a short (<70-year) rotation, and/or favor spruce over fir during intermediate treatments (Hart 1963, Westveld 1946).

Natural stand-replacing disturbances are rare in the Acadian Forest Region. Partial disturbances resulting from windthrow and isolated pockets of insects and disease are common. The spruce budworm, an insect with cyclic outbreaks that causes mortality and growth suppression in balsam fir and spruce species, has a significant impact on forest structure and composition (MacLean 1984). Budworm mortality is positively related to the proportion of fir and poor-vigor trees (Baskerville 1975a, McLintock and Westveld 1946), drainage and hybrid index (Osawa 1989), and tree age (MacLean 1980, 1984). The relationship between stand structure and budworm susceptibility is less certain, and both even-aged structures (Baskerville 1975b) and uneven-aged structures (Crawford 1984, Crawford and Jennings 1989, Westveld 1946) have been recommended. When an outbreak is at full strength, however, it may not matter because many ecological and stand relationships noted with spruce budworm at other times simply disappear (Osawa 1989).

Though the budworm promotes the release of advance regeneration and thus naturally rejuvenates mature spruce-fir stands (Baskerville 1960), outbreaks threaten short-term production capacity (MacLean 1984). Protection through spraying, although effective with regard to maintaining production, may reduce the outbreak interval by maintaining higher populations of host species (Baskerville 1975b).

The Acadian Forest has a long history of use by human beings. Virgin, or unharvested, forest is restricted to a few remote areas likely atypical of the region as a whole. Repeated diameter-limit cutting began in the 1800s and has continued until the present day (Cary 1896; Kenefic and Nyland 2005; Seymour

1992, 1995; Westveld 1928). Preferential harvesting of large trees and desired species has resulted in a forest that is currently only 9 percent large sawtimber with a softwood to hardwood ratio of 0.7:1 while the underlying forest habitat suggests that ratio should be 1.6:1 (McWilliams et al. 2005). Harvesting in response to the spruce budworm outbreak of the 1970s and 1980s contributed to these imbalances.

Silvicultural Systems

A review of silvicultural concepts and terminology will set the stage for understanding and interpreting the long-term experiment on the PEF. Silviculture is the art and science of controlling the establishment, growth, composition, health, and quality of forest stands to meet specific objectives on a sustainable basis. Silvicultural systems are planned series of treatments for tending, harvesting, and regenerating stands (Helms 1998).

Even-aged Silviculture

Even-aged silviculture is applied to create and maintain stands with a single age class of trees. The even-aged regeneration methods include clearcut, seed tree, and shelterwood, and differ in terms of the source of regeneration and amount of cover provided during stand initiation.

Clearcutting allows regeneration to be established from seed or sprouts after the overstory is removed. It is not effective for natural regeneration of shade-tolerant species, which will likely be outcompeted by fast-growing shade intolerants in an open stand. Additionally, research on the PEF has shown that northern conifer seed in the forest floor remains viable for only 1 year and is thus not a reliable source of regeneration following clearcutting (Frank and Safford 1970). The seed tree method, which leaves scattered residual trees for the sole purpose of providing seed for the new cohort, is also not effective for the shade-tolerant conifers because the intolerant hardwoods outcompete them and the shallow-rooted residuals lack windfirmness (Frank and Bjorkbom 1973, Seymour 1995). The seed tree method has been applied with

some success for eastern white pine (Wendel and Smith 1990), a companion species in many northern conifer stands, but does not provide overhead protection from the white pine weevil (*Pissodes strobi*).

The most effective even-aged regeneration method in northern conifers is shelterwood (Brissette and Swift 2006, Seymour 1995). In this method, the overstory is removed in two or more stages over the course of several years, providing seed and shade for the new cohort. This method can be used to regenerate dense stands of shade-tolerant trees, though the choice of seed trees, length of the overstory removal period, and intensity of the harvests determine the degree of shade and thus species composition of the new stand.

Additionally, shelterwood may be used to create two-aged stands if reserves, or trees from the older cohort, are retained after the regeneration harvest for reasons not related to regeneration. This shelterwood method may be implemented to increase growth and value during the next rotation, enhance vertical structure, improve aesthetics, and provide large trees for snags or downed logs (Nyland 2002).

Thinning is an intermediate treatment applied to immature even-aged stands to reduce stand density in order to improve overall growth of the stand or of individual trees, or capture mortality. These treatments may be precommercial, done as an investment before the trees are merchantable, or commercial. The timing, intensity, and type of thinning all vary depending on management objectives. The types of commercial thinning commonly applied (dominant, crown, and low thinning [Smith et al. 1997]) vary in terms of the crown classes from which trees are cut. Thinning of dominants (previously “selection” thinning) is used to remove poor form or otherwise undesirable dominants and should be applied only once to avoid high-grading (the removal of the most commercially valuable trees, often leaving a residual stand composed of trees of poor condition or undesirable species composition [Helms 1998]). Crown thinning is used to release

desired crop trees in codominant and dominant canopy positions. Low thinning, which is generally lighter and more frequent, is applied to capture mortality in the intermediate and overtopped crown classes. Research on stand response to various combinations of timing, intensity, and types of commercial thinning has only recently begun in the northern conifer type (Wagner et al. 2002), although research on the PEF has established the positive effects of precommercial thinning (PCT) on species composition, growth, and mortality (Brissette et al. 1999; Weiskittel et al. 2009, 2011).

Uneven-aged Silviculture

Uneven-aged silviculture is used to create and maintain stands with three or more age classes of trees and is accomplished via selection cutting. The selection system has traditionally been applied to create a specific diameter distribution that is believed necessary for balancing growth and removals, and is manifest in long-term consistency and sustainability of structure and production (Meyer 1952, O’Hara 1996). Structural goals are defined in numerous ways, though primarily using empirical structures from previous experiments (e.g., Arbogast 1957) or mathematical derivations (Meyer 1952, Nyland 2002, Smith et al. 1997).

The mathematical structures, such as q , have the advantage of being easy to use, but their relevance to biological processes is debated (Davis 1966, Oliver and Larson 1996). The approach historically applied on the PEF is the BD q method (Fiedler 1995, Guldin 1991, Marquis 1978), in which a target residual basal area (BA), maximum diameter (D), and q -factor are determined based on financial or biological maturity, residual stocking goals, and desired distribution of growing stock among saplings, poles, and sawtimber (Kenefic and Brissette 2001). Using multiple q -factors to define a single structure has been suggested (Hansen and Nyland 1987, Leak and Filip 1975). The higher the q , the more growing stock in the smaller size class, and vice versa. The higher the basal area goal, the more trees in each size class, without any change in the proportional distribution of trees.

The often-cited advantages of uneven-aged silviculture include comparatively little soil disturbance, high vertical structural diversity, high canopy cover, and continuous production of high-value sawlogs (Nyland 2002, Smith et al. 1997, Troup 1928). The last objective is best met through the application of structural goals that allocate a high proportion of growing space to the sawtimber classes. This approach is supported by research on the PEF that found that upper canopy trees generally produce more stemwood per unit leaf area than those lower in the canopy (Seymour and Kenefic 2002). However, too much overstory will suppress the development of poletimber and may impede regeneration and growth of small trees. The amount of overstory that can be carried without suppressing smaller trees to the point of structural instability has yet to be determined for northern conifers, though species' competitive advantage is clearly related to amount and quality of overstory light (Moores et al. 2007). Data from the PEF demonstrate that even trees released from suppression do not grow as well as those that have been free growing; that is, older trees in the uneven-aged stands grow less stemwood per amount of foliage than younger trees do (Seymour and Kenefic 2002). Unfortunately, preliminary assessment of sapling ingrowth dynamics in the uneven-aged PEF stands revealed slow growth and high mortality, generating additional questions about long-term sustainability (Kenefic and Brissette 2005).

Although it is critical not to have too many trees in the sawtimber classes of uneven-aged northern conifer stands, it is also important not to create imbalances in other portions of the stand structure. The recommended diameter distribution should be followed for two reasons: to provide sufficient trees in each size class to replace those from larger classes as they grow in size or are cut, and to moderate growth of smaller trees (Arbogast 1957, Solomon and Frank 1983). Though timely regeneration of desired species is necessary to sustain uneven-aged stands, quality and distribution of growing stock should not be overlooked. In particular, it is necessary to tend immature trees in order to accumulate high-quality

growing stock (Hart 1963). Thus, a deficit in the mid-size classes, for example, both endangers sustainability of production as the sawtimber-sized trees are removed, and results in poor control over growth in the sapling classes.

Short-term sacrifices in quality and growth may be necessary for attainment of structural goals, particularly during periods of conversion to an uneven-aged condition or rehabilitation of unmanaged or mismanaged stands (Nyland 2002). This approach is due in part to the need to sustain old trees in order to maintain an uneven-size structure during conversion (Nyland 2003). It has been suggested that such losses could be minimized in extreme cases by reducing the residual stocking goal (i.e., BA), and correspondingly lengthening the cutting cycle (Nyland 1987, 2002). This type of action would be short-term only and has the disadvantages of a delayed next entry and some loss of control over mortality and quality due to the longer cutting cycle.

The regeneration method utilized in uneven-aged silviculture is the selection method. Selection cuttings are applied on a fixed cutting cycle to remove mature timber, tend the immature classes, and establish new regeneration (Nyland 1987). The distribution of removals is across all size classes and may be single-tree or in groups. Furthermore, though age and size are assumed to be equivalent, and thus size structures are utilized instead of age structures, research on the PEF has demonstrated that this relationship is poor in multi-aged stands of shade-tolerant species (Blum 1973, Kenefic and Seymour 1999b, Seymour and Kenefic 1998). However, the extreme difficulty of determining tree age from phenological characteristics of a tree requires use of the traditional diameter distribution but justifies exploratory age analysis and adjustment of growth expectations and structural goals based on the results of such.

Within the confines of the allowable cut per size class as determined by the structural goal defined above, removals are distributed to improve growth, quality, and species composition (Frank and Blum

1978, Leak et al. 1969). In traditional application, it is important that desires to make short-term gains in these factors do not jeopardize longer-term attempts to create a balanced structure. In applying such a treatment, species composition goals and marking guides are important, and all trees for harvest should be marked under the supervision of an experienced selection marker. The use of designated skid trails and directional felling are desirable because of the potential for residual stand damage associated with repeated partial harvests (Baker and Bishop 1986).

Much remains unknown about the short- and long-term dynamics of growth in managed uneven-aged northern conifer stands. Many questions of interest to researchers and practitioners, such as whether there is a production advantage to utilizing uneven- instead of even-aged silviculture, cannot be answered until both systems have been applied in a single experiment for the equivalent of a full rotation (approximately 80-100 years in northern conifers). The PEF and the Acadia Research Forest in New Brunswick are the only locations with long-term experiments in the selection system in the Acadian Forest, and among few such sites in the world.

Exploitative Cutting

Exploitative cutting occurs when trees are removed without regard for residual stand condition. This type of harvesting occurs when short-term volume and value removals are given priority over long-term sustainability of composition and structure (Kenefic and Nyland 2005, Nyland et al. 1993). The intensity of the harvest varies, and ranges from diameter-limit cutting, in which valuable trees above specific size thresholds are removed, to commercial clearcutting, in which all merchantable trees are removed from a stand without tending or attention to regeneration (thus, as described here, commercial clearcutting is different from clearcutting as a silvicultural treatment). Both are examples of high grading, removing the most valuable trees from the stand. Though commonly practiced, removal-driven harvesting is rarely experimentally applied. The PEF is the site of the oldest known replicated experiment in diameter-limit

and commercial clearcutting of northern conifers, and research on the PEF has documented the degrading effects of these practices on residual stand condition (Kenefic and Nyland 2005, 2006; Kenefic et al. 2005a).

It has been theorized that stands subjected to repeated diameter-limit cuts will develop a structural imbalance that will ultimately suppress the establishment of regeneration and prevent periodic harvests (Roach 1974). Modeling work in northern hardwoods has suggested a number of negative impacts, including reduced stand value, structural imbalance, and species and quality degradation (Nyland 2005, Nyland et al. 1993). However, along with the experiment on the Fernow Experimental Forest in West Virginia (Schuler et al. 2005) and studies installed in the Central Hardwood Region (Fajvan 2006), the studies on the PEF are among the few sources of information about the results of experimentally controlled exploitative cutting. Though results from the PEF demonstrate shifts in species composition, degraded stand value, loss of sawtimber production, and increases in the proportion of unmerchantable trees, it is not yet known whether the repeated partial entries can be sustained. Modeling suggests, however, that the PEF fixed diameter-limit cut stands will not sustain another harvest of equal volume for many years (Kenefic et al. 2005a).

Researchers in the Central Hardwoods have suggested an alternative to fixed diameter-limit cutting called modified (flexible) diameter-limit cutting. This alternative is similar to guiding diameter-limit cutting, which was developed for loblolly-shortleaf pine in the southern United States (Guldin 1987, Reynolds et al. 1984), although the allowable cut in modified diameter-limit cutting may not be restricted to growth as it is in guiding diameter-limit cutting. Because removals are based on pre-determined size thresholds, modified diameter-limit cutting does not create or maintain a specific residual condition. However, it is regarded by some as a compromise that allows landowners to accumulate the benefits of selection cutting without the necessity of tending the

unmerchantable classes (Miller and Smith 1993). As applied on the PEF, this treatment differs from fixed diameter-limit cutting in that trees below the diameter limits may be harvested if they are expected to die, and trees above the diameter limits may be left for wind protection or seed production. Preliminary analysis of data from the PEF suggests that stands treated with modified diameter-limit cutting are more similar to selection stands than to fixed-diameter-limit cut stands, and that these differences become more apparent over time (Kenefic et al. 2004).

Stand Development

Stand development is the competitive process of tree initiation, growth, senescence, and death (Smith et al. 1997). It is important for managers to be familiar with expected stand development patterns when they are applying silvicultural treatments and assessing stand response. These patterns, described by Oliver (1981) and Oliver and Larson (1996), provide an ecological basis for understanding and communicating stand growth. In even-aged stands resulting from stand-replacing disturbances, stands move sequentially through four stages: stand initiation, stem exclusion, understory reinitiation, and (in unmanaged stands) old growth. When this terminology is used to describe stand development, even people unfamiliar with the forest type may understand the processes and structures in the stands. Definitions (from Oliver 1981 and Oliver and Larson 1996) are as follows:

- Stand initiation: Begins when a disturbance removes the existing stand and makes growing space available for a new cohort, and continues as long as trees are establishing.
- Stem exclusion: Begins when sufficient leaf area develops to prevent new cohorts from establishing, and continues as long as new cohorts are excluded. At this stage the processes of differentiation into crown classes (dominant, codominant, intermediate, and overtopped) and self thinning occur, and intermediate treatments and/or regeneration cuttings are applied.

- Understory reinitiation: Begins when gaps in the canopy (from crown abrasion or tree mortality) allow new cohorts to establish. An old-growth stand will result, unless a disturbance, such as harvesting, occurs. This is the stage when regeneration cuttings are often applied.
- Old growth: Begins when all trees from the initial cohort have died, and normally is not reached in stands managed for commodity production.

In uneven-aged stands the stem exclusion and understory reinitiation stages will likely occur in different places within the same stand at the same time. Additionally, in both even- and uneven-aged mixed-species stands, stratification occurs due to differences among species in height growth patterns, shade tolerance, and longevity, resulting in increased structural complexity.

With this background on the Acadian Forest, silviculture, and stand development to provide context, we now consider the details of the long-term silvicultural experiment on the PEF.

METHODS

Treatment Overview

The PEF long-term silvicultural experiment involves 10 treatments (Table 1), each replicated twice in a completely random experimental design (Fig. 2). The compartments (now called management units in the PEF study) average 21 acres in size and the experiment covers 418 acres of the approximately 3,900-acre PEF. Considering that most of the compartment management studies established in the 1950s on experimental forests were either abandoned or scaled back, the long-term experiment on the PEF stands out for having remained true to its original intent. Harvest activities and sample plot remeasurements have stayed close to schedule throughout the life of the experiment (Fig. 3). In the early 2000s, the measurement interval between harvests was increased from 5 years to 10 to accommodate measurement of several additional response variables.

Table 1.—Treatments and compartments to which they are applied on the Penobscot Experimental Forest

System	Treatment		Management Unit
	Code	Description	
Even-aged silviculture	SW2	Uniform shelterwood, 2-stage overstory removal	21, 30
	SW3	Uniform shelterwood, 3-stage overstory removal; without precommercial thinning	23b, 29b
	SW3 PCT	Uniform shelterwood, 3-stage overstory removal; with precommercial thinning	23a, 29a
Uneven-aged silviculture	S05	Single tree and group selection, 5-year cutting cycle	9, 16
	S10	Single tree and group selection, 10-year cutting cycle	12, 20
	S20	Single tree and group selection, 20-year cutting cycle	17, 27
Exploitative cutting	CC	Commercial clearcutting	8, 22
	FDL	Fixed diameter-limit cutting	4, 15
	MDL	Modified diameter-limit cutting	24, 28
Reference	REF	Unmanaged reference	32a, 32b

Treatment Descriptions

Prior to treatment initiation, the study area was dominated by a second-growth forest of irregular age and size structure (Fig. 4a,b). Though land-use history before 1950 is not well documented, descriptions on maps indicate that it was “mixed softwood second growth” with pole-size spruce and fir, hemlock up to sawtimber size, scattered hardwoods, and good spruce and fir regeneration in 1929, and “operable spruce-fir-hemlock” in 1949¹. These conditions most likely resulted from a long history of periodic partial cutting and subsequent natural stand development (Kenefic et al. 2006, Sendak et al. 2003).

The first study plan (McLintock 1953) presented the silvicultural treatments as a range of management options from “poor” to “high-order” and specified tentative residual stand structural and compositional

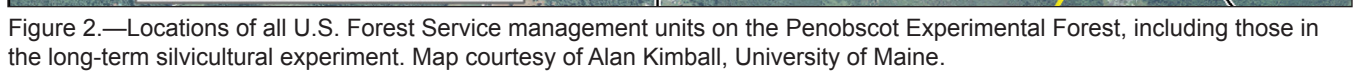
goals as a basis for experimentation. Subsequent revisions of this plan by Hart (1962) and Frank (1975) clarified the silvicultural terminology and specifics of the treatments. The status of the treatments and current prescriptions, per the most recent study plan revision (Brissette and Kenefic 2008), are outlined in the following descriptions.

Even-Aged Silvicultural Treatments

Shelterwood System, Two-Stage Overstory

Removal (SW2): This treatment is replicated in management units 21 (27 acres) and 30 (18 acres) (Fig. 2). In both management units the final overstory removal was completed in 1967 (Fig. 3), leaving well-established advance regeneration and an average of 77 trees per acre in the 5-inch and larger diameter at breast height (d.b.h.) classes. The stands have two-storied structures with the larger residuals in the upper stratum. The new cohort reached the stem exclusion stage of stand development by the 1990s. Although the new cohort would benefit from removing

¹ Unpublished documents on file at the Penobscot Experimental Forest and available from the authors.



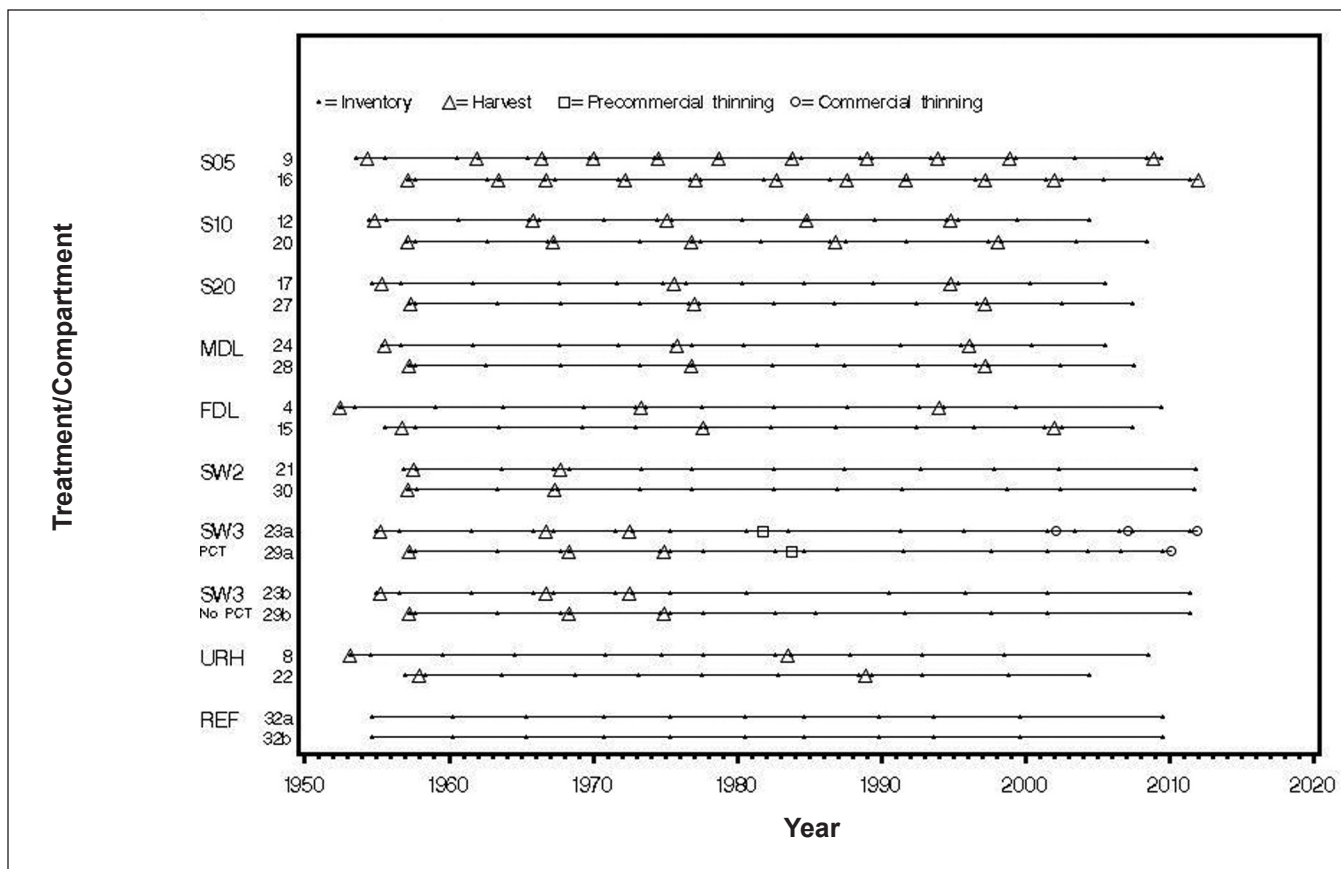


Figure 3.—Timeline of treatments and inventories in the long-term silvicultural experiment on the Penobscot Experimental Forest through 2011.

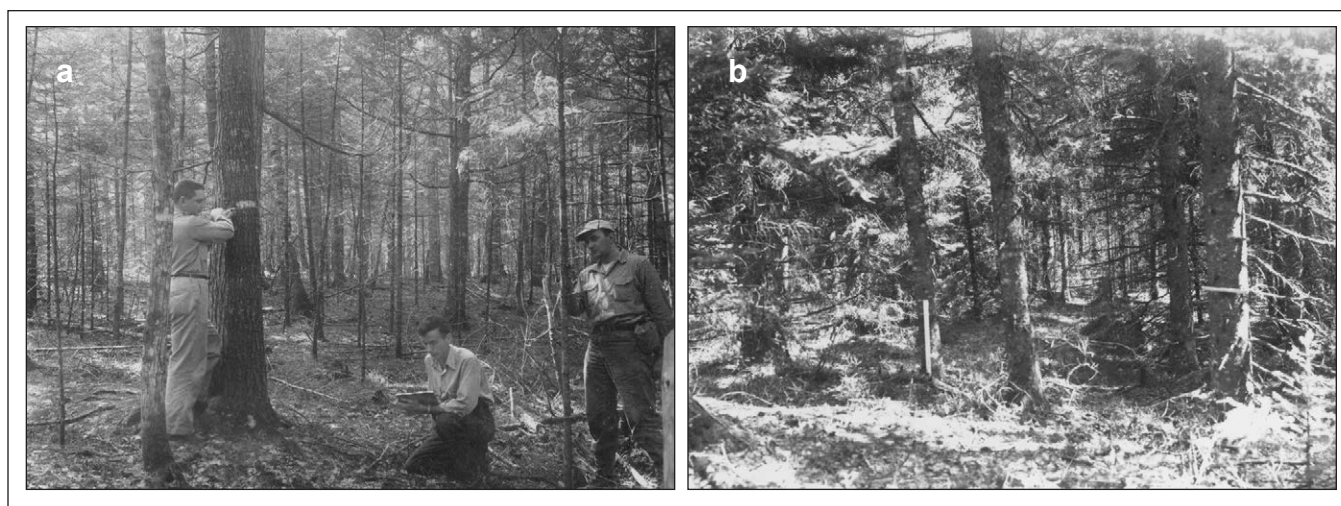


Figure 4a,b.—Forest composition and structure prior to initiation of the long-term silvicultural experiment on the Penobscot Experimental Forest in the 1950s. Photos by U.S. Forest Service.

the overtopping residuals, there has not previously been enough merchantable volume to support a commercial thinning. The next planned intervention in this treatment will be a thinning. The authors and cooperators are working on a thinning prescription that will be applied in the next year or so; overstory BA will be reduced by no more than 40 percent.

Shelterwood System, Three-Stage Overstory

Removal (SW3 and SW3 pct): The final overstory removal in MU23 was in 1971, and in MU29 in 1974 (Fig. 3). Unlike SW2, all residual trees >2.5 inches in d.b.h. were cut during or immediately after the final overstory removal. About 10 years after the overstories were removed, these management units were split into approximately equal areas. Half of each management unit received PCT and half was left to develop without PCT.

Shelterwood System, Three-Stage Overstory

Removal without PCT (SW3): The replicates for this treatment are MU23b (12 acres) and MU29b (8 acres) (Fig. 2). Both stands are in the stem exclusion stage of development, and self thinning is occurring. A thinning will be applied in this treatment when there are sufficient merchantable-sized trees in the new cohort to support a commercial harvest.

The likely thinning prescription will focus on maximizing stand-level volume production (see Seymour 1999) while also releasing high-quality eastern white pine and spruce crop trees from competition. The thinning method used will be a combination of crown and low thinning to capture mortality and release crop trees. Crown class, species, live crown ratio, and stem form and quality will be used to identify trees for either removal or retention.

Shelterwood System, Three-Stage Overstory

Removal with PCT (SW3 pct): This treatment is replicated in management units 23a (12 acres) and 29a (9 acres) (Fig. 2). Manual PCT to a residual spacing of approximately 6 feet by 9 feet was applied

in MU23a in 1983 and in MU29a in 1984 (Fig. 3). The PCT lengthened the period of stand initiation and allowed new seedlings to become established. It enhanced diameter growth on the residual trees enough that these stands were further subdivided and commercially thinned. Both were included in the University of Maine's Commercial Thinning Research Network (Seymour et al., this volume). MU23a and MU29a were commercially thinned in 2001 and 2010, respectively (Fig. 3).

Uneven-Aged Silvicultural Treatments

Selection System, 5-Year Cutting Cycle (S05):

Replicates of this treatment are MU9 (27 acres) and MU16 (16 acres) (Fig. 2). The eleventh selection cutting was in 2009 in MU9, and in 2011 in MU16 (Fig. 3). Stands are vertically and horizontally diverse, with areas in both stem exclusion and understory reinitiation. The stands are highly stratified, and trees within each stratum are differentiated into crown classes.

The 2008 study plan revised the BD q structural goal to reflect species-specific growth rates and longevity. The previous version of the study plan did not account for species differences and had only one target diameter distribution ($q=1.96$ on 1-inch d.b.h. classes) and maximum diameter (MaxD, 19 inches d.b.h.) for the treatment. When all species are combined, the q for this treatment now averages 1.6 (decreasing from 1.8 in the saplings to 1.4 in the large sawtimber) and stand-level MaxD (excluding eastern white pine emergents) is 22 inches d.b.h. Species composition goals were also modified to better reflect the species assemblage occupying the site (the target BA was lowered for spruce and increased for hemlock). Efforts are being made to sustain spruce and reduce structural bimodality (too few trees in poletimber classes and too many in sawtimber) through increased recruitment and reduction of sawtimber excesses. An excess of seedlings and saplings has reduced the need to establish regeneration, and PCT is conducted to release spruce saplings from within-stratum competition.

Species composition goals, expressed as a proportion of BA ≥ 4.5 inches d.b.h. are as follows:

- eastern hemlock, 30 percent
- spruce species, 40 percent
- hardwoods, 15 percent
- balsam fir, eastern white pine, and northern white-cedar (*Thuja occidentalis* L.), 5 percent each

Marking guidelines by order of priority are:

- remove cull trees, except northern white-cedar unless it exceeds the stand-level composition goal and/or is negatively impacting the growth of a merchantable tree
- remove high-risk trees (i.e., trees expected to die before the next entry)
- remove unacceptable growing stock (UGS; trees without potential for volume or value increase)
- remove trees from d.b.h. classes and species that are in excess relative to the goals
- release or thin potential crop trees in the sapling, pole, and small sawtimber classes
- remove trees beyond species MaxD

Trees are not cut from size classes that are deficient relative to the diameter distribution unless they fall into the cull, high-risk, or UGS classifications. Trees with active cavities are not cut, nor are trees that will damage a snag with active cavities when felled. One to two trees greater than MaxD may be retained per management unit, if of exceptional size and quality for their species.

Target residual BA is 105 ft²/acre ≥ 4.5 inches d.b.h., and the difference between actual and target stand BA in the 4.5-inch d.b.h. and larger classes equals the allowable cut. If allowable cut is less than 5 ft²/acre (i.e., 1 ft²/acre \times cutting cycle length in years), then harvest is delayed until the next scheduled entry.

For structural control, the following species groups and maximum diameters are recognized:

- eastern hemlock and spruce species, 22 inches d.b.h.
- balsam fir, 10 inches d.b.h.
- northern white-cedar, 12 inches d.b.h.
- hardwoods, 18 inches d.b.h.
- eastern white pine, 24 inches d.b.h.

Selection System, 10-Year Cutting Cycle (S10): This treatment is replicated in management units 12 (31 acres) and 20 (21 acres) (Fig. 2). The fifth selection cutting was applied in 1994 in MU12, and in 1998 in MU20 (Fig. 3). Stands are vertically and horizontally diverse, with areas in both stem exclusion and understory reinitiation. The stands are highly stratified, and trees within each stratum are differentiated into crown classes.

Like the 5-year selection, this treatment had a single q -factor (1.96) and MaxD (18 inches d.b.h.) prior to the 2008 study plan revision. When all species are combined, the q for this treatment now averages 1.6 (decreasing from 1.8 in the saplings to 1.4 in the large sawtimber) and stand-level MaxD (excluding eastern white pine emergents) is 20 inches d.b.h. Species composition goals and marking guidelines are the same as for the 5-year selection, and PCT is conducted to release selected spruce saplings.

Target residual BA is 90 ft²/acre ≥ 4.5 inches d.b.h., and the difference between actual and target stand BA in the 4.5-inch d.b.h. and larger classes equals the allowable cut. If allowable cut is less than 10 ft²/acre (i.e., 1 ft²/acre \times cutting cycle), then harvest will be delayed until the next scheduled entry.

For structural control, the following species groups and maximum diameters are recognized:

- eastern hemlock and spruce species, 20 inches d.b.h.
- balsam fir, 8 inches d.b.h.

- northern white-cedar, 12 inches d.b.h.
- hardwoods, 16 inches d.b.h.
- eastern white pine, 24 inches d.b.h.

Selection System, 20-Year Cutting Cycle (S20):

The replicate management units for this treatment are MU17 (26 acres) and MU27 (20 acres) (Fig. 2). The third selection treatment was applied in 1994 in MU17, and in 1996 in MU27 (Fig. 3). Stands are vertically and horizontally diverse, with areas in both stem exclusion and understory reinitiation. The stands are highly stratified, and trees within each stratum are differentiated into crown classes.

Like S05 and S10, this treatment had a single q -factor (1.96) and MaxD (16 inches d.b.h.) prior to the 2008 study plan revision. When all species are combined, the q for this treatment now averages 1.6 (decreasing from 1.8 in the saplings to 1.4 in the large sawtimber) and stand-level MaxD (excluding eastern white pine emergents) is 18 inches d.b.h. Species composition goals, use of PCT, and marking guidelines are the same as those for the 5- and 10-year selection treatments.

Target residual BA is 70 ft²/acre \geq 4.5 inches d.b.h., and the difference between actual and target stand BA in the 4.5-inch d.b.h. and larger classes equals the allowable cut. As in the other selection treatments, if allowable cut is less than 20 ft²/acre (i.e., 1 ft²/acre \times length of cutting cycle), then harvest will be delayed until the next scheduled entry.

For structural control, the following species groups and maximum diameters are recognized:

- eastern hemlock and spruce species, 18 inches d.b.h.
- balsam fir, 6 inches d.b.h.
- northern white-cedar, 10 inches d.b.h.
- hardwoods, 14 inches d.b.h.
- eastern white pine, 22 inches d.b.h.

Exploitative Cutting

Commercial Clearcut (CC): Replicates of this treatment are management units 8 (43 acres) and 22 (34 acres) (Fig. 2). These management units were initially cut in 1953 (MU8) and 1957 (MU22); the second harvests were in 1982 and 1988 (Fig. 3). All merchantable trees were removed; lower merchantability standards resulted in heavier cuts in the second entries. The stands are in the stand initiation and stem exclusion phases of development. Portions of the management units in this treatment are being used to study a range of stand rehabilitation techniques (Kenefic et al. 2010).

Fixed Diameter-Limit Cutting (FDL): This treatment is replicated in management units 4 (25 acres) and 15 (26 acres) (Fig. 2). The third diameter-limit cut was applied in MU4 in 1992 and in MU15 in 2001 (Fig. 3). Though some areas are in stem exclusion, much of the stand area is in the stand initiation phase. These management units will be harvested again when stand volume reaches initial (pre-first cut) treatment volume (2,000 ft³/acre). At that time all merchantable trees at and above the following species-specific diameter limits will be cut:

- eastern white pine, 10.5 inches
- spruce species and eastern hemlock, 9.5 inches
- paper birch and northern white-cedar, 7.5 inches
- all other species, 5.5 inches

Modified Diameter-Limit Cutting (MDL): The two replicates of this treatment are MU24 (26 acres) and MU28 (18 acres) (Fig. 2). The third modified diameter-limit cut was applied in MU24 in 1995 and in MU28 in 1996 (Fig. 3). Portions of the stands are in the stem exclusion and understory reinitiation stages of development.

Unlike the fixed diameter-limit treatment, where the harvest interval depends on stand dynamics, this treatment has a defined cutting cycle of 20 years. Furthermore, the diameter-limit classes are flexible, not proscriptively rigid as they are in the

fixed diameter-limit treatment. Consequently, at the next harvest entry all merchantable trees above the following species-specific diameter-limit classes will be cut unless they are needed for a seed source or to provide wind protection for smaller trees:

- eastern white pine and spruce species, 14.5 inches
- eastern hemlock, 12.5 inches
- paper birch, 9.5 inches
- northern white-cedar, 7.5 inches
- all other species, 6.5 inches

Trees below the diameter limits may be harvested if they are expected to die before the next entry.

Experimental Control

Unmanaged Reference (REF): The reference replicates, MU32a (13 acres) and MU32b (6 acres), were originally one management unit, which was split in 1993 to take into account the distinctly different stages of stand development and to balance the experimental design. The stages of stand development were distinct because of an unrecorded natural disturbance event about the time the study was established that affected the area differently. MU32a is in the stand initiation and stem exclusion phases of development while MU32b is in the latter stages of stem exclusion and will soon enter the understory reinitiation phase. Neither management unit has been harvested since the late 1800s; prior to that, selective partial cuts were made.

Response Variables

Response variables are measured on a series of PSPs established at the beginning of the study. Currently there are 295 PSPs or, on average, one plot for each 1.4 acres of the experiment. These nested circular fixed-radius plots have a common center point. Plot size varies depending on the size of tree or variable measured. Within these plots are three permanent circular milacre plots for inventorying regeneration in the treated management units and four such plots in the reference. Response variables are measured

before and after harvests. The current study plan calls for additional inventories at 10-year intervals between harvests. (S05 and S10 have no between-harvest inventories because of their cutting cycles.) Previously, that interval was 5 years. (S10 did have between-harvest inventories then.) It was changed to accommodate measuring additional response variables without adding substantially to the inventory workload. The current response variables are:

Species: Regardless of size, trees are recorded to species. Woody shrubs such as willow (*Salix* spp.), alder (*Alnus* spp.), and hazel (*Corylus* spp.) are not measured, even though they sometimes reach tree stature.

Regeneration: For each milacre plot the substrate is recorded as: undisturbed forest floor, disturbed forest floor, mineral soil, down coarse woody material, logging slash, rock, or water. If more than one substrate is present, the percentage of each is estimated to the nearest 10 percent. For tree species the number of seedlings >6 inches tall is counted according to height class: 0.5 to <1.0 foot, 1.0 to <2.0 feet, 2.0 to <4.5 feet, and ≥4.5 feet with d.b.h. <0.5 inches.

Understory vegetation: The milacre plots are also used to estimate percentage of cover of non-tree vegetation. Each milacre plot is visualized as a cylinder rising through the canopy, and the relative abundance for various taxa is classified within the cylinder (Witham et al. 1993). Non-tree taxa are recorded as: woody shrubs, herbaceous vegetation, grasses and sedges, ferns and similar plants, and mosses and lichens.

Diameter at breast height: Diameter at breast height is measured at 4.5 feet above the ground to the nearest 0.1 inch using a diameter tape. Tree size determines which plot it is measured on, as follows:

D.b.h. (inches)	Plot size (acres)
0.5 to <2.5	1/50
2.5 to <4.5	1/20
≥4.5	1/5

Diameter at breast height (continued): Since the mid 1970s, trees for which d.b.h. is measured have been numbered individually and a horizontal line is painted on the side of the tree facing plot center. Thus individual trees are followed over time and d.b.h. is consistently remeasured at the same location on the stem. Under the current measurement regime, more than 40,000 trees are measured in a typical year. In September 2010, the one-millionth d.b.h. measurement of a numbered tree was taken (Fig. 5).

Spatial Distribution: On a subsample of at least 30 percent of the plots in each management unit, the location of each numbered tree ≥ 4.5 inches d.b.h. is determined in relation to plot center, to the nearest 0.1 foot and nearest 2° of azimuth. The same plots are remeasured in subsequent inventories to add ingrowth trees and follow mortality.

Tree Height and Crown Attributes: On the same subsample of plots used to establish spatial distribution, height and crown attributes are measured on the sampled (i.e., spatially located) trees, as follows:

Total height—Measured to the nearest 0.1 foot.

Height to base of live crown—Measured to the nearest 0.1 foot. In this study, the base of the live crown is the center of the lowest live

branch where it intersects the bole of the tree.

The lowest live branch is the lowest branch that appears to be contributing more than it receives from the rest of the crown.

Crown projection—Distance from the center of the bole of each measured tree to the edge of its crown is measured to the nearest 0.1 foot in the four cardinal directions.

Tree Condition: A condition code is assigned to each numbered tree at each inventory. The codes provide information about the tree's size class and general health and quality. Condition codes include such information as whether a tree is alive or dead (and the cause of mortality), whether it is ingrowth (first time measured as a sapling or pole-size tree) or was previously measured, and whether it is merchantable or cull. After trees ≥ 4.5 inches d.b.h. die, they stay in the inventory and the condition code reflects whether they are standing or down snags, and their state of decay.

DESIGN AND ANALYSIS

The study is laid out in a completely randomized experimental design (i.e., 2 replications of the 10 treatments). Management units are the experimental units. Response variables are measured on the PSPs. On average there are 15 PSPs per management unit.

The reference was not included in the original experimental layout. It was added in 1954, after the experimental treatments were assigned to management units but before all initial treatments were applied. It is not contiguous with the rest of the experiment. However, because it is the best reference area we have to compare with the treated management units, it is considered an experimental control in analyses.

Data collected in this study are entered into a relational database before the next field season; details can be found in Russell et al. (this volume). In addition, an archived online database is maintained and is readily available to researchers working on the study and cooperators interested in testing various hypotheses or building models of northern conifer stand dynamics (Brissette et al. 2012).



Figure 5.—Project leader John Brissette takes the one-millionth measurement in the long-term silvicultural study on the Penobscot Experimental Forest in 2010, assisted by a student technician (center) and forester Rick Dionne. Photo by U.S. Forest Service.

OUTCOMES AND FUTURE DIRECTION

Results from the long-term silvicultural experiment on the PEF have improved our understanding of forest ecology and influenced the way forests are managed both regionally and internationally. Unlike most earlier silvicultural studies, the PEF long-term experiment was replicated and included an array of silvicultural systems. Research was initially restricted to sapling-size and larger trees, but that deficiency was recognized early on and measures of regeneration were added in the mid-1960s. Researchers quantified the competitive advantage of balsam fir over red spruce due to fir's larger and less palatable seed (Abbott and Hart 1961), more frequent seeding, deeper rooting, and faster growth (Hart 1963). It became clear that natural regeneration of northern conifer stands was prolific, but questions remained about how to achieve desirable species mixtures. The spruce species were found to be less abundant than fir and hemlock under a range of selection and other partial cutting intensities, and hardwood-to-softwood ratios were higher in treatments with comparatively heavier removals (Brissette 1996).

Results of this study have been the basis of silvicultural guidance to forest managers. "The Silvicultural Guide for Spruce-Fir in the Northeast" (Frank and Bjorkbom 1973) has been used extensively by industrial, private, and government foresters throughout the northeastern United States and Atlantic Canada. In addition, management recommendations specific to uneven-aged silviculture were developed from the PEF selection treatments (Frank and Blum 1978). Findings after 20 years of treatment showed decreases in the amount of unmerchantable volume, increases in seedling density and proportions of spruce, and improved diameter distributions.

The uneven-aged (selection) system was emphasized during the initial planning of the PEF study due to the shade tolerance of the most important commercial species and the preponderance of Forest Service partial cutting research prior to World War II (Westveld 1946). Variants of even-aged systems were included in

the experiment at the urging of David M. Smith from Yale University, who was asked to review a draft of the study plan. He told McIntock that "management and harvesting of spruce-fir types in this country would become pretty badly hog-tied in detailed refinements if an honest effort were made to superimpose the true selection principle..."² A national paradigm shift to even-aged silviculture focusing on high-yield, low-cost wood production occurred around 1960 (Seymour et al. 2006), largely because uneven-aged silviculture was regarded by many foresters as unnecessarily complex, prone to high-grading, and ill-suited for maximizing wood production. Thus, Smith's suggestion to include even-aged treatments on the PEF proved to be an inspiration as studies of fertilization, PCT, strip clearcutting, whole-tree harvesting, and planting were initiated on the PEF between the 1960s and 1980s in direct response to the nationwide shift in forestry thinking. Because of the treatment design, the long-term silvicultural experiment on the PEF has demonstrated that northern conifer stands can be managed effectively with both uneven- and even-aged silvicultural systems, giving managers a broad range of options. That is not the case in most forest types.

The emphasis on even-aged silviculture began to wane in many parts of North America by the 1990s, when the idea of New Forestry ("a kinder and gentler forestry that better accommodates ecological values") (Franklin 1989: 38) started to influence how both researchers and managers approached silviculture. On the PEF, the descriptor "spruce-fir" gave way to the more inclusive (and more accurate) "northern conifers" and new response variables were added to the long-term study, including standing and downed snags; structural characteristics such as tree location, height, crown projection, and crown length; and ground cover. Treatment prescriptions started emphasizing wildlife trees and canopy emergents by excluding a significant portion of them from cutting.

² Smith, D.M. 1952 (November). Letter to T.F. McIntock. On file at the Penobscot Experimental Forest and available from the authors.

In 1994, the industrial owners of the PEF donated the property to the University of Maine Foundation with the hope that new research would be initiated by faculty and graduate students. In the donation document they stated their expectation that the PEF would “afford a setting for long-term research conducted cooperatively among U.S. Forest Service scientists, University researchers and professional forest managers in Maine; to enhance forestry education of students and the public; and to demonstrate how the timber needs of society are met from a working forest.”³ With greater involvement by University researchers, the number of short-term studies overlain on the Forest Service’s long-term experiment has increased. These studies usually have a basic rather than applied focus and cover a range of topics important to sustainable forest management, including: wood decay (Smith et al. 2007), leaf area and growth efficiency (Kenefic and Seymour 1999a, Maguire et al. 1998, Seymour and Kenefic 2002), leaf morphology and gas exchange (Day et al. 2001), carbon storage (Hoover 2005), herbivory (Larouche et al. 2010), bird and insect diversity and habitat suitability (Johnston and Holberton 2009, Su and Woods 2001), and genetic diversity (Hawley et al. 2005).

Studies of dead standing trees have provided new insights into the dynamics of wildlife habitat. Snag longevity, for example, was found to be a function of species, size, stand density, and cause of death, and was greatest in unharvested stands and least in stands with short cutting cycles (Garber et al. 2005). Investigation of decayed down wood established the importance of this substrate for regeneration of spruce and hemlock (Weaver et al. 2009). The effect of silviculture on spatial arrangement of trees was also investigated. Regeneration events were found to increase aggregation and reduce species mingling, particularly when treatment shifted species composition toward hardwoods (Saunders and Wagner 2008).

³ Unpublished document on file at the Penobscot Experimental Forest and available from the authors.

Although non-tree vegetation received limited attention on the PEF in the past, an inventory of understory vegetation on the PSPs in the long-term study was recently completed. Understory species richness and diversity generally declined with decreasing silvicultural intensity (determined by BA removed and time since cutting); differences in diversity and composition of understory plants were related to canopy composition and forest floor disturbance (Bryce 2009). Nonnative invasive plants were uncommon in the experimental stands but abundant in adjacent old-field stands (Olson et al. 2011).

The long-term silvicultural experiment on the PEF provides a unique perspective on forest dynamics, a perspective that is increasingly more relevant with time. One of the advantages of long-term experiments is that scientists can document treatment responses that vary over time. For example, the diameter distributions of the PEF selection treatments were close to their goals in the 1970s and researchers predicted that the stands would remain “essentially balanced” (Frank and Blum 1978). However, analysis of data from later remeasurements revealed structural and compositional imbalances that were not apparent in earlier assessments (Kenefic and Brissette 2001, Seymour and Kenefic 1998). In addition, though increases in the proportion of spruce growing stock led Frank and Blum (1978) to conclude that efforts to favor those species were successful, we now know that this outcome was a function of accretion rather than recruitment (Kenefic et al. 2007). Spruce trees in the selection treatments are almost all more than a century old (Seymour and Kenefic 1998) and new saplings have been growing at a rate of less than 1 inch in diameter per decade.⁴

Similarly, growth rates of seedlings in the selection treatments have been slow; the shade-tolerant conifers can take as many as 35 years to reach 1.5 feet in height (Weaver 2007). Analysis of relationships between

⁴ Unpublished data on file at the Penobscot Experimental Forest and available from the authors.

overstory stocking and growth of understory trees in the selection treatments revealed that there was no level of canopy closure that favored spruce over its competitors (Moores et al. 2007). These findings tell a story much different from those of the 1970s, and raise concerns about long-term sustainability of structure and composition of the selection treatments. These concerns can be addressed only by continuing to implement planned treatments and measuring the results over the next few decades.

In general, understanding of how forests respond to disturbances increases with time, but we must acknowledge that the localized impacts of climate change are still largely speculative. Iverson and Prasad (2001) concluded from their models that spruce-fir forests will be extirpated from New England within the century. Dawson et al. (2011) contend that although such models help identify exposure to climate change, assessing consequences requires considering not only exposure but sensitivity and adaptive capacity as well. Sensitivity is the degree to which the persistence and fitness of a species or species group depends on a particular climate. Adaptive capacity refers to whether species or communities tolerate change, shift their habitats, migrate to new regions, or become extinct (Dawson et al. 2011).

Little is known about the sensitivity and adaptive capacity of northern conifers, but long-term experiments like the one on the PEF offer the best empirical evidence for evaluating the effects of climate change on these qualities. Studying phenotypic plasticity, genetic diversity, ecophysiology, and silvical traits like seed dispersal and microhabitat preferences can tell us much about the sensitivity and adaptive capacity of northern conifers. Many of these traits can be measured, and are being measured, in the PEF long-term experiment. In fact, many of these traits have been measured over the past 60 years (see Kenefic and Brissette, this volume) but not in the context of climate change. Evaluating how silvicultural treatments influence sensitivity and adaptive capacity will be a high priority for the PEF long-term silvicultural experiment over the next several decades.

SUMMARY

The long-term silvicultural study on the PEF has spanned the careers of four generations of researchers and has influenced the education and practices of untold numbers of foresters and other natural resource professionals, as well as landowners, from across the region. Field tours of the experiment are always dynamic events with many questions and much discussion. Two of the most frequently asked questions are: “What is the most important thing learned so far?” and “Why is it important to continue the study?”

Our answer to the first question is rather straightforward: *Healthy, productive forests are maintained through careful harvesting based on informed planning. Harvesting for immediate gain alone leaves behind a low-quality forest with few options for the future.*

Both even- and uneven-aged methods influence the composition and structure of northern conifer stands and thereby provide valuable timber, high-quality habitat, aesthetically pleasing views, and a broad range of management options for the future. However, management focused on short-term financial returns alone leaves stands that have few high-quality trees and require decades of growth before they once again provide a range of management options. In short, silviculture matters.

The answer to the second question is more subjective but perhaps more important: *Knowledge accumulated through continued research leads to better, more certain management decisions.*

Researchers turn data into knowledge. Managers turn knowledge into action. Knowledge based on short-term results is incomplete at best and often wrong. The value of knowledge increases as it accumulates in two important ways: greater precision for prescribing treatments and greater certainty that prescriptions will achieve desired results. The PEF study is now more than halfway through an even-aged rotation and the overstory of the uneven-aged treatments is still

composed mostly of trees that were there when the experiment began. Consequently, we must continue to evaluate stand development patterns following the various treatments in order to provide managers the level of precision and certainty needed to ensure success.

This experiment represents a tremendous investment in time, effort, and dollars. It is also logical and appropriate to ask whether it has been worth it. We believe that it has, and that it continues to be worthy of our time and talents. Results of this study are of interest to a wide audience. Studies of underlying ecological processes and qualities like sensitivity and adaptive capacity with regard to climate change advance science and are presented via scientific meetings and peer-reviewed journal articles. Applied results such as management guidelines improve how forests are managed and are presented at practitioner-oriented meetings and in publications. Additionally, field tours of the experiment are a key component of the technology transfer program on the PEF. This experiment not only has influenced the practice of forestry in the northern conifer type, but more importantly, has helped advance understanding of tree and stand growth and the relationship between human and natural disturbance at a fundamental level, not specific to a forest type. We maintain that the value of this study will continue to increase as its results are used to address the always-evolving compelling questions of the day.

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APPENDIX I.

Conversion of English to metric values for units used in this paper.

Multiply	by	to obtain
Inches (in.)	2.54	Centimeters (cm)
Feet (ft)	0.3048	Meters (m)
Acres (ac)	0.4047	Hectares (ha)
Trees per acre (TPA)	2.471	Trees per hectare (TPH)
Square feet per acre (ft ² /ac)	0.2296	Square meters per hectare (m ² /ha)
Cubic feet per acre (ft ³ /ac)	0.06997	Cubic meters per hectare (m ³ /ha)

APPENDIX II.

Examples of recent short-term studies in the U.S. Forest Service Long-Term Silvicultural Experiment on the Penobscot Experimental Forest, 1994-2010.

Name	Topic	Date Completed	Degree	Advisor	Institution
Part 1. Graduate Student Research					
Daniel Gilmore	Crown structure, stem form, and leaf area relationships for balsam fir	1995	Ph.D.	Robert Seymour	University of Maine
Geoffrey Wilson	Modeling early regeneration processes in mixed-species forests	1997	M.S.	Douglas Maguire	University of Maine
Jeffrey Jaros-Su	Insect biodiversity in managed forests	1999	Ph.D.	Stephen Woods	University of Maine
Laura Kenefic	Leaf area, stemwood volume growth, and structure in mixed-species, multi-aged stands	2000	Ph.D.	Robert Seymour	University of Maine
Michael Day	Factors influencing net primary production in red spruce	2000	Ph.D.	Michael Greenwood	University of Maine
Kerry Sokol	Effects of long-term diameter-limit cutting on radial growth and genetic diversity	2001	M.S.	Michael Greenwood	University of Maine
Suzhong Tian	Effects of precommercial thinning on root structure	2002	Ph.D.	William Ostrofsky	University of Maine
Leah Phillips	Crop-tree growth and quality after precommercial thinning	2002	M.S.	Robert Seymour	University of Maine
Andrew Moores	Understory growth dynamics and mensuration techniques in uneven-aged, mixed-species stands	2003	M.S.	Robert Seymour	University of Maine
R. Justin DeRose	Leaf area index - relative density relationships in even-aged balsam fir - red spruce stands	2004	M.S.	Robert Seymour	University of Maine
Spencer Meyer	Leaf area as a growth predictor of balsam fir and red spruce	2004	M.S.	Robert Seymour	University of Maine
Margaret Ward	Age-related trends in red spruce needle anatomy and the relationship to declining productivity	2005	M.S.	Michael Greenwood	University of Maine

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Appendix II (continued)

Name	Topic	Date Completed	Degree	Advisor	Institution
Michael Saunders	Dynamics of forest structure under different silvicultural regimes	2006	Ph.D.	Robert Wagner	University of Maine
Stephanie Adams	Age-related decline in photosynthesis in red spruce	2006	M.S.	Michael Day, Michael Greenwood	University of Maine
Brent Horton	Reproductive behavior of the white-throated sparrow	2007	Ph.D.	Rebecca Holberton	University of Maine
Jamie Weaver	Regeneration and substrate availability in partially cut stands	2007	M.S.	Laura Kenefic	University of Maine
Jason Johnston	Effects of forest management and food availability on condition and breeding of hermit thrushes	2007	Ph.D.	Rebecca Holberton	University of Maine
Robert Lindemuth	Sampling methods for estimating basal area and volume in partially harvested stands	2007	M.S.	Thomas Brann	University of Maine
Ashley Thomson	Comparative phylogeography of North American birches	2009	M.S.	Christopher Dick	University of Michigan
Catherine Larouche	Regeneration of northern white-cedar in partially cut mixedwood stands	2009	Ph.D.	Jean-Claude Ruel, Laura Kenefic	Laval University
Elizabeth Bryce	Influence of silviculture and site on native and nonnative forest understory plant distribution	2009	M.S.	Laura Kenefic	University of Maine
Katherine Spencer	Red spruce photosynthesis and maturation	2009	M.S.	Michael Day	University of Maine
Matthew Olson	Temporal and spatial patterns of tree regeneration	2009	Ph.D.	Robert Wagner	University of Maine
Christopher Zellers	Growth and financial performance of eastern white pine reserve trees	2010	M.S.	Robert Seymour	University of Maine
Kate Zellers	Patterns of eastern white pine regeneration as influenced by reserve trees	2010	M.S.	Robert Seymour	University of Maine

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Appendix II (continued)

Principal Investigator(s)	Topic	Date completed	Institution
Part 2. Examples of Additional Short-Term Research			
John Brissette	Red spruce and hemlock stem volume	1997	U.S. Forest Service, Northern Research Station (NRS)
Robert Shepard	Wood properties in thinned and unthinned stands	1997	University of Maine
Doug Maguire et al.	Crown structure and growth efficiency of red spruce	1998	University of Maine
Laura Kenefic, Robert Seymour	Age-size relationships in managed uneven-aged stands	1998	U.S. Forest Service, NRS University of Maine
Alison Dibble et al.	Understory vegetation and red spruce regeneration	1999	U.S. Forest Service, NRS University of Maine
Gary Hawley et al.	Genetic implications of diameter-limit cutting	2000	University of Vermont U.S. Forest Service, NRS
Mark Ducey et al.	Point relascope sampling of down woody material	2003	University of New Hampshire U.S. Forest Service, NRS
Shawn Garber et al.	Snag longevity in managed stands	2005	Oregon State University University of Maine
Coeli Hoover	Carbon sequestration in thinned stands	2006	U.S. Forest Service, NRS
Aaron Weiskittel et al.	Effect of precommercial thinning on tree and stand characteristics	2009	University of Maine U.S. Forest Service, NRS
Bruce Cook et al.	Ecosystem structure and dynamics	ongoing	NASA
John Bradford et al.	Relationship of climate and silviculture to tree growth response	ongoing	U.S. Forest Service, NRS
Laura Kenefic et al.	Rehabilitation options for cutover mixedwood stands	ongoing	U.S. Forest Service, NRS University of Maine
Sam Droege, Jim Guldin	Native pollinators	ongoing	U.S. Geological Survey U.S. Forest Service, SRS
Walter Shortle, Jody Jellison	Biology and biochemistry of wood decay	ongoing	U.S. Forest Service, NRS University of Maine