Chapter 5
Northeastern Conifer Research: Multiple Species and Multiple Values

Laura S. Kenefic, John C. Brissette and Richard W. Judd

Abstract The northern conifer, or spruce-fir, forest of the northeastern USA and adjacent Canada has had a defining influence on the economy and culture of the region. The same can be said of the USDA Forest Service's research in this forest, which began more than 100 years ago. Forest Service research has evolved since that time in response to changes in the needs and prominence of the forest industry, and in public attitudes and concerns. Early studies of forest protection and rehabilitation first gave way to mid-century research on production forestry, then to twenty-first-century research on forest ecology. Though various lines of research have come and gone, long-term studies on the region's experimental forests continue to provide a unique perspective on the structure and dynamics of the forest, and the outcomes of silvicultural alternatives.

Keywords Acadian Forest · Penobscot Experimental Forest · Silviculture · Red spruce · Balsam fir

5.1 Background

A magnificent forest coupled with a complex of favorable environmental conditions made the Northeast a leader in lumber and pulpwood production in the 1800s and early 1900s (e.g., see Wilson 2005). Though forest industry provided an economic boon to the region, widespread cutting of progressively smaller trees resulted in forest degradation and raised concerns about resource sustainability (Judd 1997). At the time of his appointment as Chief of the US Division of Forestry (now the USDA Forest Service) in 1898, Gifford Pinchot observed that the heavy utilization of northeastern forests had "affect[ed] the forest to its injury" (Pinchot 1898, p. 31).

L. S. Kenefic (✉)
Northern Research Station, USDA Forest Service, Bradley, ME 04411, USA
Phone: (207) 581-2794
e-mail: lkenefic@fs.fed.us

J. C. Brissette
Northern Research Station, USDA Forest Service, Durham, NH, USA

R. W. Judd
Department of History, University of Maine, Orono, ME, USA

D. C. Hayes et al. (eds.), *USDA Forest Service Experimental Forests and Ranges,*
DOI 10.1007/978-1-4614-1818-4_5, © Springer New York 2014

In fact, by the end of the nineteenth century, the forests of the Northeast were a patchwork of brush, sprout-wood, relic old-growth, and second-growth timber.

Heavy cutting continued throughout the region in the early twentieth century, and opposition to exploitative practices intensified (Judd 1997). In response to industry pressure for continued production and public concerns about forest degradation, the Forest Service initiated research in the Northeast on forest rehabilitation, management, and protection. This research program was formalized by the creation of the Northeastern Forest Experiment Station (now the Northern Research Station) in 1923. Over the years, research by the Forest Service has evolved in response to changes in resource demands and the prominence of forest industry, and to changes in society's values and expectations. The focus of this chapter is the Forest Service's trajectory in northern conifer research over the following periods:

Resource assessment (1890s–1920s)
Forest improvement (1920s–1940s)
Changing directions (1940s–1950s)
Postwar prosperity (1950s–1990s)
Diversification (1990s–present)

5.2 Research Program

5.2.1 The Forest

Though northern hardwoods predominate in the Northeast, the northern conifer forest is locally abundant and was the primary source of wood for early industrial endeavors. This forest extends from the Adirondacks in New York through northern New England into maritime Canada (Fig. 5.1). Much of this forest is in the transitional zone between the eastern broadleaf and boreal forests and contains a diverse mixture of softwoods and hardwoods. Red spruce (*Picea rubens*) is largely confined to this region and is its signature species. Tolerant of shade, slow growing, and having excellent wood properties, this important commercial species is commonly known for its stiff and sharply pointed needles and woodsmen's confectionary "spruce gum." White (*P. glauca*) and black (*P. mariana*) spruces are also common, but the most prolific softwood in the region is balsam fir (*Abies balsamea*; Seymour 1995). Balsam fir is fast growing and competitive, but because it is more prone to insects, diseases, and decay, it is short lived relative to other shade-tolerant conifers. Consequently, it is less desirable than the spruces for most commercial products other than pulpwood.

Eastern hemlock (*Tsuga canadensis*) and eastern white pine (*Pinus strobus*) are abundant in the southern part of the forest; northern white-cedar (*Thuja occidentalis*) is more common in the north. Hardwoods include red maple (*Acer rubrum,* which leaf peepers love for its vibrant fall foliage and foresters grudgingly admire for its ubiquity and prolific sprouting), aspen (both *Populus grandidentata* and *P. tremu-*

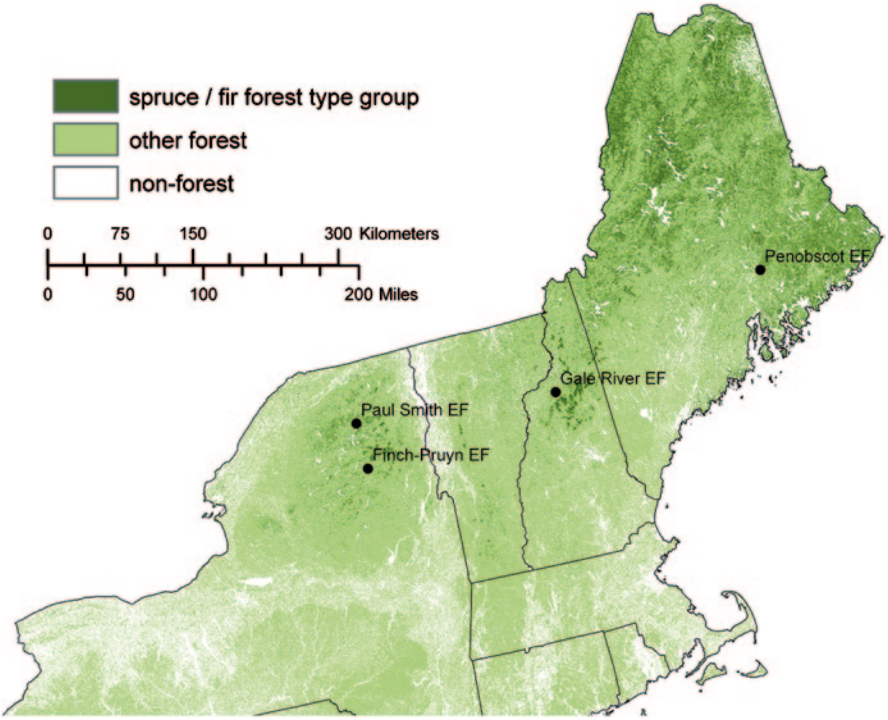


Fig. 5.1 Map of the northern conifer (previously call spruce-fir) forest in the northeastern USA. (Courtesy of B. Tyler Wilson, USDA Forest Service, Forest Inventory and Analysis)

loides), American beech (*Fagus grandifolia*), paper birch (*Betula papyrifera*) and gray birch (*B. populifolia*). Red oak (*Quercus rubra*), sugar maple (*A. saccharum*), and yellow birch (*B. alleghaniensis*) are found in better sites. Natural disturbances are primarily small scale, resulting from single-tree mortality and windthrow. Periodic larger-scale disturbances arise from insect infestation, such as the spruce budworm (*Choristoneura fumiferana*), and hurricanes (Seymour et al. 2002).The aspens, birches, oak, and pine are primarily associated with disturbances that open the forest canopy, while the other species commonly occur in closed forests. Though historically called spruce-fir, much of the forest is mixedwood; researchers in the region today call this the northern conifer forest. An important component of the northern conifer forest is the Acadian Forest (Rowe 1972), which includes most of the Canadian provinces of New Brunswick, Nova Scotia, and Prince Edward Island, as well as parts of eastern and northern Maine (Braun 1950).

One characteristic that sets the northern conifer forest apart from most other managed forests in North America is the tolerance to shade of many of the dominant species, and most of the important commercial tree species. In most regions, forest management focuses on shade-intolerant and mid-tolerant species, but northern conifer forest management emphasizes regenerating and favoring shade-tolerant trees.

The silvics of the species and predominantly small-scale natural disturbance regime result in a forest that is structurally and compositionally complex. These characteristics have important ramifications for stand dynamics and for the research that informs management of those stands.

5.2.2 The Experimental Forests

Though Forest Service researchers conducted a number of studies in the Northeast in the late 1800s and early 1900s, station leadership identified experimental forests as the preferred approach for forestry research beginning in the 1920s. Research on experimental forests was more secure and efficient than research on cooperators' lands, permitted intensive data collection, and facilitated correlation of different lines of investigation (USDA Forest Service 1935).This was a rather new idea; the first Forest Service experimental forest in the nation, the Fort Valley Experimental Forest, had been established just over a decade earlier near Flagstaff, AZ (Adams et al. 2008). The first experimental forest in the Northeast was the 754-ha (1,863-ac) Gale River Experimental Forest (GREF) on the White Mountain National Forest in New Hampshire; work there began in 1926. This was followed in the northern conifer type by the 252-ha (622-ac) Finch-Pruyn Experimental Forest (FPEF) in 1934 and 890-ha (2,200-ac) Paul Smith Experimental Forest (PSEF) in 1945; both were in the Adirondacks. In 1950, the Forest Service established the last northern conifer experimental forest, the 1,538-ha (3,800-ac) Penobscot Experimental Forest (PEF) in Maine.

5.2.3 Research Trajectory

5.2.3.1 Resource Assessment (1890s–1920s)

The earliest Forest Service research in northern conifers began in the late 1800s, predating the experimental forests. This work consisted of empirical studies aimed at characterizing the forest type and its component species, with an emphasis on red spruce. Very little was known about the condition and growth potential of the northern conifer forest, or about the impacts of logging. Early publications by Gifford Pinchot (1898), Henry Graves (1899), Ralph Hosmer (1902), Raphael Zon (1914), and Louis Murphy (1917) are characteristic of this period, which continued in the Northeast for about three decades. The objectives of these studies were to determine the condition of the forest (e.g., size- and age-class distribution, quality, vigor, and species composition), the silvical properties and growth potential of individual species and trees, and the influence of site on these characteristics. Most importantly, this work highlighted the consequences of uncontrolled logging and the growth potential of small, suppressed softwoods if protected from damage during harvesting

Fig. 5.2 Marinus Westveld (*left*), the Father of Spruce-Fir Silviculture

operations and free of hardwood competition. These observations led to recognition of the need for forest management and forest management research, and prompted the Forest Service to establish experimental forests and initiate manipulative studies in the Northeast.

5.2.3.2 Forest Improvement (1920s–1940s)

The first manipulative studies in the northern conifer type were motivated both by concerns about forest sustainability and by the desire to support economically important forest industries. In the 1920s, the northeastern pulp and paper industry manufactured more than half the nation's wood pulp and contributed substantially to the region's social and economic welfare (Meyer 1929; Westveld 1938). A rise in pulpwood prices earlier in the twentieth century had resulted in heavy cutting of spruce and fir, leaving understocked stands of poor form and defective softwoods and associated hardwoods (USDA Forest Service 1937, 1938). The forests and forest industries of the Northeast were under stress. Researchers, practitioners, industrial owners, and the public wanted to know how continuing demands for wood products could be met from the degraded forest, and how forest values could be protected. To that end, early studies on experimental forests focused almost exclusively on stand improvement and rehabilitation.

The first studies on the GREF were directed by silviculturist Marinus Westveld, now known as the Father of Spruce-Fir Silviculture (Berven et al. 2013; Fig. 5.2). Westveld's work investigated the use of partial cutting (then called "selective" cutting) to establish shade-tolerant softwood regeneration and accelerate the growth of crop trees. He also studied planting, weeding, release, and swamp drainage to improve production of spruce and fir. He put considerable effort into understanding how to secure shade-tolerant softwood regeneration in mixedwood stands with hardwood competition, and how to increase the proportion of sawtimber in managed stands. With Westveld's cooperation, similar research was initiated at the FPEF (Recknagel et al. 1933) and at the PSEF, where forester John Curry was investigating techniques for establishing regeneration and improving stand conditions.[1]

Forest Service researchers on the northern conifer experimental forests advocated the use of silviculture—the science of controlling forest establishment, growth, composition, and health—and generally focused their studies on improving forest composition and restoring production potential. Experiments that were started during this time were unreplicated and limited in scope, with a tendency to emphasize partial cutting. In this regard, research on the experimental forests established the potential of uneven-aged silviculture in the northern conifer type (e.g., Belotelkin et al. 1942; Westveld 1938), but did little to advance other types of silviculture such as even-aged systems. This emphasis was consistent with national trends in research; the period between 1925 and 1960 has been called the "selective cutting era" to reflect the near single-minded national focus on the selection system and other forms of partial cutting (Seymour et al. 2006; Smith 1972). Nevertheless, work on the experimental forests during this time demonstrated the feasibility of establishing spruce and fir seedlings prior to removing the overstory, using mechanical or chemical treatments to release overtopped softwoods (Westveld 1930, 1931) and retaining sawtimber in managed stands (Recknagel et al. 1933). This attention to advance regeneration, control of hardwood competition, and growing stock retention remain hallmarks of northern conifer silviculture today.

5.2.3.3 Changing Directions (1940s–1950s)

Despite a strong early start by station scientists working on northern conifer forest management research, change was in the wind. On September 21, 1938, the New England Hurricane made a landfall on Long Island, NY, USA with one of the highest forward speeds ever documented for a tropical cyclone (Grossi 2008). This fast-moving storm brought powerful rain and winds deep into New England, causing widespread flooding, wind damage, destruction of property and loss of forest growing stock. This hurricane was one of most destructive storms in the history of the USA, leveling nearly 7 million m^3 (250 million ft^3) of timber on more than 200,000 ha (almost 500,000 acres) of forest land. The winds were most destructive in central New England, where nearly one half of the total volume of softwood timber was destroyed, leaving behind "tangled heaps of splintered trunks and limbs piled like giant match sticks and waiting for sparks to turn a literal inferno loose" (Anonymous 1938, p. 252). Fifty percent of the station's northern conifer research plots in the hurricane zone were damaged (USDA Forest Service 1939). The partial cutting experiment and controls at the GREF were completely destroyed (Fig. 5.3). By the end of 1942, about 200,000 m^3 (7 million ft^3) of timber had been salvaged from the White Mountain National Forest alone (Spurr 1956).

The destruction of the GREF experiments was undoubtedly a great loss for Westveld, who had installed a 40-ha (100-acre) partial cutting experiment only 1 year

[1] Memorandum on file at the USDA Forest Service, Northern Research Station, Bradley, ME, USA.

Fig. 5.3 Damage on the Gale River Experimental Forest from the New England Hurricane in 1938. (USDA Forest Service photo courtesy of the Forest History Society)

before (Belotelkin et al. 1942). The 1938 hurricane was the beginning of the end for the GREF, which continued with limited work in the 1940s. In fact, most experimental forestry work was suspended during the 1940s as World War II shifted the national focus to meeting wartime demands for manpower and other resources. Staffing changes also occurred. Francis Rushmore took over the FPEF and PSEF, which were consolidated into the Adirondack Research Center (ARC). Though discussions to establish a new experimental forest in New England had been initiated after the hurricane, those efforts were put on hold until the disruption and turmoil of the 1940s gave way to new forest management and research paradigms.

One notable line of research by station scientists during this era was spruce budworm control through forest management. A spruce budworm outbreak in Canada had reached epidemic proportions by the late 1930s and was spreading toward the northeastern USA.[2] Westveld suggested a two-phase approach to silvicultural control: (1) pre-salvage cutting mature balsam fir to reduce imminent mortality and (2) converting mixed spruce-fir stands to predominantly spruce through selection cutting with removal of merchantable fir and poor vigor spruce (Westveld 1946). To determine the cost and feasibility of these practices, the station established large experimental cuttings on cooperators' lands throughout the northern conifer forest. In practice, treatments were a form of diameter-limit cutting with removal of all merchantable fir and sawtimber-sized spruce (McLintock and Westveld 1946). Marking was conducted during World War II by German prisoners of war. Though the study areas were not, in fact, infested by the budworm, they served as the basis for an evaluation of wind damage (McLintock 1954) and composition and growth in selectively cut stands (Hart 1956).

[2] Problem analysis on file at the USDA Forest Service, Northern Research Station, Bradley, ME, USA.

Fig. 5.4 Penobscot Experimental Forest owners, Forest Service staff, and cooperators at the forest's dedication in 1952

5.2.3.4 Postwar Prosperity (1950s–1990s)

The USA's entry into World War II challenged New England forest industries. Forest products were vital to the war effort, but the industry faced severe labor shortages, as rural workers left to join the military or seek defense jobs. The war emergency hastened mechanization of woods operations, while rationing resulted in pent-up demand for wood and paper products. After the war, forest industries in Maine reopened discussions with the station about a new northern conifer experimental forest. Nine pulp and paper and land-holding companies purchased the land in Maine that was leased to the Forest Service for the PEF (Fig. 5.4). A 1951 press release described this transaction as "the first instance in the annals of American forestry that a group of wood-using industries have united to purchase a timberland tract for lease to the government to do such work."

In 1950, the forest product industry was the largest industry in Maine in terms of product value, number of employees, and payroll. In a report of forest management research opportunities in the northern conifer type, Thomas McLintock, station silviculturist in Maine, noted that the foremost needs were to assess the financial feasibility and production potential of a range of treatments.[3] To that end, a large-scale compartment- (or stand-) level study was initiated on the PEF. Unlike earlier manipulative studies in northern conifers, this experiment was fully replicated, included an array of silvicultural systems, and has continued without interruption to the present day (Fig. 5.5). Similar work was also initiated at the PSEF in the

[3] Problem analysis on file at the USDA Forest Service, Northern Research Station, Bradley, ME, USA.

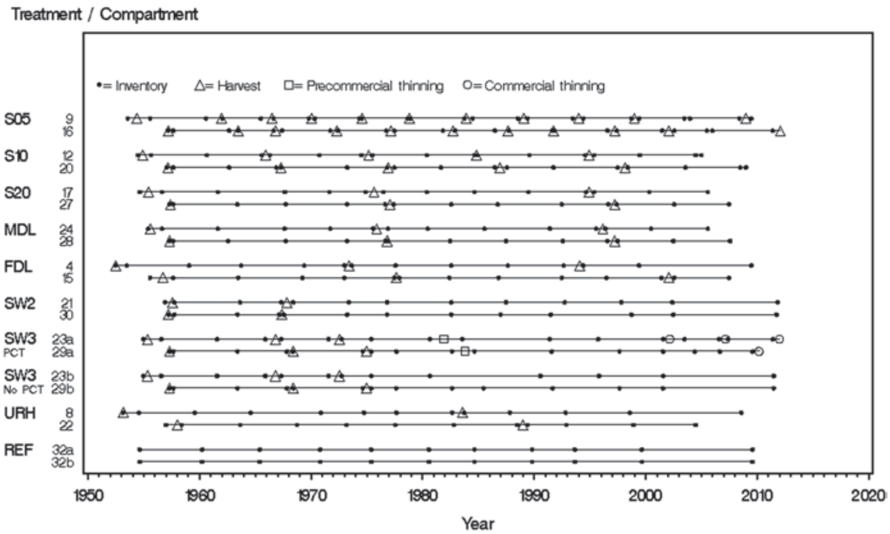


Fig. 5.5 Dates of treatment applications and inventories in the compartment study on the Penobscot Experimental Forest. Treatments are selection cutting on 5-, 10- and 20-year cycles (S05, S10, and S20), modified diameter-limit cutting (*MDL*), fixed diameter-limit cutting (*FDL*), shelterwood with two-stage overstory removal (*SW2*), shelterwood with three-stage overstory removal with and without pre-commercial thinning (*SW3 PCT* and *SW3 No PCT*), commercial clearcutting (*CC*) and no harvest (*NAT*). Numbers identify replicate compartments

Adirondacks, but was not completed. The GREF and ARC (including the FPEF and PSEF) were all closed by the early 1960s, resulting in consolidation of the station's northern conifer research program in Maine. Though the reasons for this decision were not clearly articulated, the declining relevance of earlier forest improvement research (which had been continued at the ARC; see Curry and Rushmore 1955; Rushmore 1956a, 1956b), hurricane damage at the GREF, reduced staffing, and emerging production-related research priorities were clearly contributing factors (Berven et al. 2013).

Arthur Hart, who had previously worked for Westveld on the GREF, took over the PEF research in the 1960s, and silviculturist Robert Frank Jr. joined the staff. Though research on the PEF had previously been restricted to sapling size and larger trees, Hart and Frank initiated studies of regeneration. Researchers quantified the competitive advantage of balsam fir over red spruce resulting from fir's larger and less palatable seed (Abbott and Hart 1960), more frequent seeding, deeper rooting, and faster growth (Hart 1963). It became clear that natural regeneration of northern conifers was prolific (Smith 1991), but questions remained about how to achieve desired species mixtures. Spruces 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).

Research on the PEF served as the basis for northern conifer silvicultural guidelines published during this time. These publications were typical of the Forest Service managers' handbooks and silvicultural guides that were common between the 1960s and 1980s, and which continue to serve as the basis for silvicultural prescription writing on managed lands, including national forests. Foresters throughout the northeastern USA used the *Silvicultural Guide for Spruce-Fir in the Northeast* (Frank and Bjorkbom 1973) and companion audio-slide program. This guide, which was based on PEF research results, is still being referenced today. 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 growing stock, and improved diameter distributions.

Though the uneven-aged (selection) system was emphasized on the PEF due to the most important commercial species' shade tolerance and Westveld's partial cutting research during the forest improvement era (e.g., Belotelkin et al. 1942; Recknagel et al. 1933; Westveld 1938, 1953), variants of even-aged systems were added to the experiment at the urging of cooperator David M. Smith from Yale University. Smith told McLintock 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…."[4] The experiments in even-aged silviculture became increasingly relevant to forest industries. Most industrial landowners regarded uneven-aged silviculture as unnecessarily complex, inefficient, prone to high-grading, and ill suited for maximizing pulpwood production. The national forestry paradigm shifted to even-aged silviculture, focusing on high-yield, low-cost wood production, around 1960 (Seymour et al. 2006). Smith's suggestion to include even-aged treatments in the PEF study proved to be an inspiration. Studies of planting, fertilization, thinning, strip clearcutting, and whole-tree harvesting were initiated on the PEF between the 1960s and 1980s in direct response to industrial needs. These studies were typical of Forest Service research nationwide during what is now known as the "production forestry era" (Seymour et al. 2006). The long-term silvicultural experiment on the PEF thus demonstrated that northern conifer stands can be managed effectively with both even- and uneven-aged silvicultural systems, giving managers a broad range of options.

The mid-twentieth century was a time of rapid change in harvesting technology. Retired PEF silviculturist Frank recalls that harvesting operations on the PEF transitioned from horses to modified farm tractors and bulldozers, skidders, and cut-to-length processors and forwarders during his tenure. While each of these technologies can be used for both even- and uneven-aged treatments, the physical size of early mechanical tree harvesters in Maine necessitated some form of clearcutting. Representatives of forest industries, many of whom were acting for the PEF landowners, requested that research be initiated to determine the effects

[4] Letter on file at the USDA Forest Service, Northern Research Station, Bradley, ME, USA.

of these machines on harvested sites. Because the preferred treatment at the time was strip clearcutting, Forest Service scientists established a large-scale study of this method on the PEF in the 1960s. The effects of slash disposal method, strip width, and whole-tree skidding were determined (Bjorkbom and Frank 1968), as was the nutrient status of soils in the residual stands (Czapowskyj et al. 1977). A companion study—also requested by forest industries—examined the effects of early mechanical tree harvesting on the survival of advance regeneration (Frank and Putnam 1972).

In the 1970s and 1980s, a severe spruce budworm infestation spread through southeastern Canada and northern New England. The name "spruce" budworm is misleading, because balsam fir is more susceptible than any of the spruce species. Periodic outbreaks of the budworm cause widespread defoliation, growth suppression, and mortality of fir, spruces, and even hemlock and pine at the peak of an epidemic (Blum and MacLean 1985). To salvage infested trees, reduce the amount of fir, and start a new cycle of regeneration, companies began clearcutting on a grand scale (Judd 1989). This activity created vast acreages of young, even-aged northern conifer stands and led to questions about precommercial thinning (PCT). Consequently, two PCT experiments were initiated on the PEF and would ultimately provide important information about the effectiveness of various operational methodologies and spacings. Analysis two decades after treatment revealed that crop trees in thinned stands had larger diameters, longer crowns, and higher volumes, and that thinned stands had more spruce and less fir (Brissette et al. 1999; Weiskittel et al. 2009).

Ironically, the most serious threat to long-term research on the PEF came just after this time of high research productivity. During the budworm years, Forest Service staffing had increased in Maine to include silviculturists, entomologists, soil scientists, and wildlife biologists. Despite continuing pressure from industry for forest management research, station leadership considered closing the research work unit in the late 1980s. The plan, which was intended to reduce costs, would have moved the scientific staff to New Hampshire. While the PEF research would have continued, it would have suffered without local management. After the announcement that the station might close the unit, an outpouring of support from the local forestry community convinced management to keep it open. While the overall number of staff in Maine was reduced, those assigned to the PEF were not affected. The most important outcome of the potential closing came several years later—in 1994—when the industrial landowners donated the PEF to the University of Maine Foundation.

5.2.3.5 Diversification (1990s–present)

In the 1980s and 1990s, forest industries in northern New England underwent profound changes involving consolidation, downsizing, and turnover in mill and forest ownerships. Early mills acquired large amounts of land and held it against wood shortages, but returns on this investment were low. As long as timberland was cheap, the mills retained their forest property, but with land values rising rapidly and demand for pulp declining in the 1980s and 1990s, many liquidated (Acheson 2000; Hagan et al. 2005). In some cases, the purchasers were organizations focused on preservation, conservation, or ecological forestry, such as the Nature Conservancy, which purchased 75,000 ha (185,000 acres) of International Paper Company's land along the St. John River in Maine (Acheson 2000; Irland 1999).

Increased emphasis on forest ecology had become common in forest management and research after the emergence of New Forestry, "a kinder and gentler forestry that better accommodates ecological values" (Franklin 1989, p. 38). In Maine, a number of unsuccessful citizens' referenda aimed at constraining forest management activities; the advent of forest certification and changing forest age-class structure motivated changes in the type and extent of silvicultural manipulations. On the PEF, the forest-type descriptor "spruce-fir" gave way to the more inclusive (and more accurate) "northern conifers." Frank began a new irregular shelterwood treatment with the objectives of creating multi-cohort stands and retaining large trees for cavities, snags, and downed woody material. The new project leader John Brissette added new measurement variables to the compartment study, including standing dead and downed trees, structural characteristics, such as tree location, height, crown radii, and crown length, and ground cover.[5] Laura Kenefic joined the project as a silviculturist and revised the stand prescriptions to exclude wildlife trees and some canopy emergents from cutting in the silvicultural treatments, and incorporated tree age into analysis of the selection treatments.

In 1994, the industrial owners of the PEF donated the property to the University of Maine Foundation, with the hope that faculty and graduate students would initiate new research. The station's earlier plan to close the research work unit played a part in the owners' decision to divest the property. 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."The Forest Service continued its research under a formal agreement, and encouraged collaboration between station and university scientists. In 1994, university scientists initiated the Acadian Forest Ecosystem Research Program, a long-term, multidisciplinary study on the effects of expanding-gap silviculture based on small-scale natural disturbance patterns (Saunders and Wagner 2005). This study was designed to complement the existing Forest Service experiment.

After the PEF became affiliated with the university, the number of short-term studies overlain on the Forest Service's long-term experiment increased. The earliest of these focused on ecophysiology, including photosynthesis, leaf morphology, leaf area, and growth efficiency (Day 2000; Kenefic and Seymour 1999; Maguire et al. 1998; Gilmore and Seymour 1996). The unique age structure of the PEF

[5] Study plan on file at the USDA Forest Service, Northern Research Station, Bradley, ME, USA.

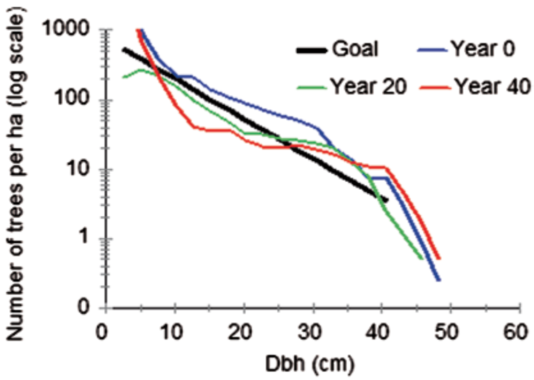
selection stands, in which trees of the same species and age are in both suppressed understory and dominant overstory positions, allowed investigation of the effects of age on various growth parameters. Research by Forest Service staff and university collaborators revealed the negative effects of tree age—independent of tree size—on photosynthetic rate (Day et al. 2001) and the efficiency of stemwood volume growth (Seymour and Kenefic 2002). The influences of silvicultural treatments on tree-level growth dynamics were also investigated. The effect of PCT on root and height growth, for example, was found to be greater for balsam fir than for red spruce (Tian and Ostrofsky 2007; Weiskittel et al. 2009), suggesting that increases in the relative proportion of spruce in thinned stands are due more to preferential release of that species than to an advantage conferred by release.

Dead trees (and even living trees leaning more than 45°) were excluded from earlier inventories on the PEF, but snags and downed woody material became a focus of study during the 1990s. New research in the long-term compartment study revealed treatment differences in the amount, size, and decay class of standing dead and downed woody material (Garber et al. 2005; Weaver 2007). Decayed downed wood was found to be an important regeneration substrate for spruce and hemlock, but not for balsam fir and red maple, suggesting that management of dead wood can influence regeneration composition (Weaver et al. 2009). In addition, the tree numbers and mortality codes used on the permanent sample plots in the compartment study since the 1970s proved useful for relocating dead trees and identifying their dates of death. This allowed researchers to determine snag longevity and relate it to tree species and size, silvicultural treatment, and cause of death (Garber et al. 2005).

Though woody vegetation on the PEF had been inventoried in the 1960s (Safford et al. 1969), non-tree vegetation received little attention until the 1990s, when a study of understory plant associations with red spruce regeneration was conducted (Dibble et al. 1999). More recently, a complete inventory of understory plants on the sample plots in the Forest Service compartments was completed (Bryce et al. 2008). Understory species' richness and diversity generally declined with decreasing silvicultural intensity; differences in diversity and composition of understory plants were related to canopy composition and forest floor disturbance (Bryce 2009). Non-native invasive plants were uncommon in the experimental stands, but abundant in adjacent old-field stands, suggesting that mitigation is warranted to prevent future encroachment.

Other recent cooperative studies have covered a range of topics important to sustainable management of the region's forests, including wood decay and nutrient cycling (Smith et al. 2007), soil carbon (Hoover 2005), herbivory (Larouche et al. 2010), wildlife diversity and habitat suitability (Su and Woods 2001), and genetic implications of silvicultural treatments (Hawley et al. 2005). Such studies exemplify the potential of long-term silvicultural research to evolve and address emerging topics.

Fig. 5.6 Diameter distributions in a selection treatment on the Penobscot Experimental Forest reveal that the stands were closer to the target in year 20 than in year 40 of the experiment



5.3 Synthesis of the Research Trajectory

Forest Service research in northern conifers has evolved over the last century. Relevant research from earlier eras has continued to the present day (e.g., the PEF compartment study and PCT experiments), while other lines of research have been closed as industrial needs and societal expectations changed (e.g., the GREF swamp drainage and PSEF studies of chemical debarking). Though many of the individual trees studied by our predecessors are still living, management objectives and constraints differ from those when the first northeastern experimental forests were established in the 1920s. Early efforts related to forest protection and rehabilitation were supplanted by research on productivity and production, and later by studies of forest ecology and the impacts of manipulations on ecological processes.

5.3.1 New Perspectives

Despite these changes, long-term silvicultural studies like the one on the PEF continue to provide a unique perspective on forest dynamics. One of the advantages of building upon earlier work 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, p. 11). However, later remeasurements revealed structural and compositional imbalances that were not apparent in earlier assessments (Kenefic and Brissette 2001; Seymour and Kenefic 1998; Fig. 5.6). 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 result 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). It can take more than 30 years for spruce seedlings in these stands to reach just 0.5 m (1.6 ft) in

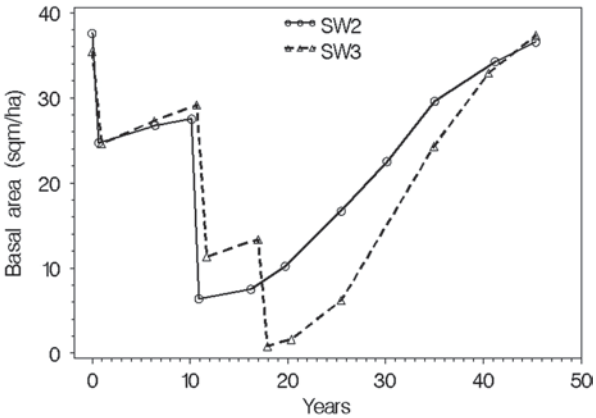


Fig. 5.7 Basal areas (trees ≥1.3 cm dbh) of the Penobscot Experimental Forest shelterwood treatments in which small and unmerchantable trees were retained (*SW2*) and removed (*SW3*). *SW3* had less growing stocking until the onset of residual mortality in *SW2*

height (Weaver 2007), and recruited saplings grow at a rate of about 2 cm (less than 1 in.) in diameter per decade.[6] Analysis of relationships between overstory stocking and growth of understory trees in the selection treatments revealed that there was no level of canopy closure favoring spruce over its competitors (Moores et al. 2007). These findings tell a much different story from those of the 1970s and raise concerns about long-term sustainability of structure and composition of the treatments.

The shelterwood treatments on the PEF have also revealed new findings over time. As an even-aged method, shelterwood has been more effective than clearcutting for regenerating shade-tolerant conifer-dominated stands. When the overstory is manipulated to provide partial shade, shade-tolerant and mid-tolerant species regenerate prolifically, while establishment of shade-intolerant species is limited. Unlike the selection treatments where sapling growth has been slow, development of shelterwood-regenerated stands on the PEF has been relatively rapid; stands grew to pretreatment levels of basal area (BA) in about 45 years (Fig. 5.7). The key difference between the selection and shelterwood treatments is that in the latter, the overstory is removed after a new cohort is established, providing full or nearly full sunlight.

The two variants of shelterwood in the long-term study on the PEF are two-stage (SW2) and three-stage (SW3) treatments; the stages are the number of harvests used to remove the overstory and release the new cohort. On the PEF, however, a partial overstory purposefully left in SW2 affected stand development more than the number of overstory removal cuts did. In SW2, more than 6 m^2/ha (approximately 28 ft^2/ac) of pole-timber and unmerchantable sawtimber were left, while in SW3, all trees ≥5 cm (2 in.) in diameter at breast height were felled (Fig. 5.7). Though SW2 had more residual BA for many years after treatment, the sparse overstory slowed development of the new cohort. By 45 years after the first (establishment) cut in both treatments, SW3 had as much BA as SW2, even though it was released later and started with almost no BA. The relatively slower growth observed in the

[6] Data on file at the USDA Forest Service, Northern Research Station, Bradley, ME, USA.

treatment with residual trees is consistent with the slow sapling growth in the selection treatments, and underscores the impact of overstory shade on the growth of young spruce and fir trees. Even though regeneration of tolerant conifers benefits from shady understory conditions for germination, seedling establishment, and early growth, full light is needed for rapid stand development.

5.4 Societal Impact

The trajectory of Forest Service research in northern conifers reveals a long history of research response to the needs of forest industry and society as a whole. Early manipulative studies were motivated not only by the desire to support the economically important forest products industries but also by public concern about degradation of the region's forests. Later investigations of production forestry were in response to the thriving economy of the postwar years and associated public demand for forest products. More recent studies of ecology and ecological forestry coincided with the regional transition of forest ownership from industry to other classes of landowners, and with society's demands for "a kinder and gentler forestry" (Franklin 1989). How, in turn, has Forest Service research affected the practice of forestry and the people of the northern conifer forest region?

Prior to the McIntire–Stennis Act of 1962, the capacity of university faculty to conduct forestry research was limited (Thompson 2004). Faculty members were concerned primarily with teaching, and had neither the funds nor the time to maintain substantial research programs. As a consequence, Forest Service studies were the sole source of information about many forest management topics. This was especially true in the northern conifer forest. Without the work of Westveld, Curry, Rushmore, McLintock, and Hart, northern conifer forest industries would have had little scientific basis for their management. Forest Service scientists developed all of the early spruce and fir silvicultural guides, yield tables, silvics manuals, and volume and site index equations. As such, the Forest Service can be credited for almost all of the early advances in northern conifer forest management, including the early twentieth-century transition from clearcutting to partial harvesting, the widespread practice of hardwood control in mixedwood stands via mechanical and chemical treatments, and the practice of establishing and protecting advance regeneration in stands managed for shade-tolerant conifers. Since that time, the Forest Service's collaboration with universities throughout the region has resulted in the frequent use of experimental forests, including the PEF, for laboratory exercises, student employment, and graduate research. In this way, Forest Service researchers on the experimental forests have contributed to the education and training of generations of natural resource professionals.

The impact of Forest Service research on northern conifer forest policy and forestry practice was particularly apparent during the years of spruce budworm outbreaks. Forest Service staffing in Maine was at an all-time high between the late 1970s and mid-1980s. Experts such as entomologist Gordon Mott were transferred

Fig. 5.8 Results from research on selection cutting (*left*) and diameter-limit cutting (*right*) on the Penobscot Experimental Forest led to regional changes in forest policy and practice

to Maine to tackle the issue of budworm control. Widespread insecticide spraying had triggered intense controversy over the potential hazards posed to the forest environment and human health (Irland 1980). Though spray programs had covered as many as 8 million ha (20 million acres) per year and slowed tree mortality, the need for repeated treatment led many to believe that they were ultimately futile. In response to these concerns, Forest Service researchers and cooperators developed an approach in which management objectives and stand conditions were used as guides for harvesting and targeted spraying (Dimond et al. 1984). Adoption of this practice by forest industries had a profound impact on northern conifer management at the time, and helped to reduce the exposure of northern forests and communities to potentially harmful chemicals.

More recently, assessments of long-term data from the PEF diameter-limit cutting and selection treatments resulted in changes in forest practices and policy throughout the Northeast and adjacent Canada (Fig. 5.8). Diameter-limit cutting as applied on the PEF (called fixed diameter-limit cutting, FDL) is the selective removal of large trees, without tending or deliberately establishing regeneration. Because FDL is easy to apply and results in high-value removals in the short term, it is widely practiced throughout North America. Though anecdotal evidence suggested that FDL was not sustainable, there were no data in the literature to support this claim. Analysis of the FDL and selection treatments on the PEF after 50 years of study revealed that repeated applications of diameter-limit cutting had resulted in lower stand volume and value, more unmerchantable timber, less medium-large sawtimber growth, and less desirable regeneration (Kenefic et al. 2005). This work clearly established the long-term degrading effects of FDL and led to a widely used primer for landowners and policy makers (Kenefic and Nyland 2005), a regional conference for practitioners (Kenefic and Nyland 2006), and numerous policy initiatives. Results have been used by the Bureau of Indian Affairs, the Northeastern Area State and Private Forestry Forest Stewardship Program, Maine Forest Service Landowner Assistance Program, Provincial Ministry of Natural Resources in Ontario, and numerous extension offices to promote sustainable forestry throughout the region.

5.5 Future Directions

5.5.1 Penobscot Experimental Forest

In recent years, data from the Forest Service's long-term study on the PEF have increasingly been used to answer large-scale questions about natural resource management. Carbon sequestration for climate change mitigation, for example, is one of the foremost challenges facing resource managers and policy makers today, but little is known about the long-term impacts of management alternatives in many forest types. With more than 60 years of data and a full array of silvicultural systems, the PEF is ideally suited to address the carbon sequestration implications of forest management in northern conifers. Ongoing research evaluating carbon sequestration across the treatments in the compartment study (e.g., Seymour et al. 2009) will provide information critical to forest management for climate change mitigation and carbon credit accounting.

Long-term tree growth records from Forest Service research on the PEF are also being used to develop a new individual-tree, distance-independent growth and yield model for the region (Weiskittel et al. 2010). Though practitioners and forest managers commonly use growth and yield models to predict future outcomes, existing models perform poorly in complex stands (Saunders et al. 2007). Data from the PEF are being used to parameterize equations to predict tree growth (Russell and Weiskittel 2010); these equations are key drivers for ongoing efforts to estimate stand productivity in mixed-species, even-, and uneven-aged stands. In addition, measurements from the PEF have recently been used to develop crown width equations for more than a dozen species (Russell and Weiskittel 2011); accurate estimates of crown width are increasingly important due to their use in fields employing light detection and ranging (LiDAR) and other novel remote sensing technologies. Modeling efforts such as these are expected to become more prevalent in the future.

Remote sensing is now commonly used in lieu of traditional, labor-intensive, on-the-ground inventory, and serves as the basis for harvest planning, habitat evaluation, forest health assessment, and estimation of biomass and carbon at large spatial scales. It is critical that the algorithms used in these analyses, and the resulting data, are strongly correlated with actual forest condition. The Forest Service's studies on the PEF are characterized by numerous stands with a range of structures, compositions, and treatment histories, all within a relatively small area and supported by intensive data collection. As such, the PEF has proven useful for ground truthing new technologies and new applications of existing technologies, such as the use of LiDAR and L-band radar to estimate standing biomass and carbon stocks (Cook et al. 2010).

As the research work unit responsible for the PEF has grown to include 14 experimental forests from Maine to Minnesota, the number and breadth of Forest Service staff at the PEF have diminished. As a consequence, research by cooperators makes up an ever-increasing proportion of the Forest Service's northern conifer research portfolio. One of the key requirements for the success of this collaborative model is readily available long-term data. To that end, all of the data from the PEF compartment study and a number of related studies were recently brought into a relational database (Russell et al. 2014). Because of those efforts, the PEF was identified as a high-priority location for national efforts to make Forest Service research data available online. Data, metadata, and supplemental files from the PEF are publicly available on the Internet (e.g., Brissette et al. 2012), resulting in increased awareness and use of the research.

5.5.2 Cross-Site Research

Today, there are more than 80 experimental forests and ranges and associated Forest Service research sites across the USA, representing important geographic, ecologic, atmospheric, and climatic systems. The continental distribution and longevity of these sites and their records are unmatched. In the past, research programs on experimental forests such as the PEF focused on concerns of local or regional importance. Though that function remains important, these sites are being increasingly valued as platforms for studies that cross landscape and continental gradients to address regional, national, and global problems. To accomplish this vision of an integrated network, it is critical that experimental forests and ranges are linked as collaborating research sites.

A number of Forest Service synthesis projects have been initiated to address large-scale questions; the PEF is involved in three such efforts. The first is a regional synthesis of long-term results from cutting practice level (CPL) studies.[7] Starting in the 1940s, researchers at experimental forests in the Northeast installed CPL plots to demonstrate a range of silvicultural practices rated "poor" to "high order." Though treatments were generally not replicated within individual experimental forests, they were similar across the station. Data from these plots were recently compiled and will be used to assess similarities and differences in treatment outcomes across forest types.

[7] Study plan on file at the USDA Forest Service, Northern Research Station, Bradley, ME, USA.

The second synthesis project to which the PEF is contributing is a national study of pollinating insects. This project, in collaboration with the US Geological Survey, originated from a multiagency federal task force formed in response to the international perception that populations of pollinating insects are in decline. Little information about the status or trends of native bees in the USA was available despite their key role in terrestrial environments. As a consequence, a federal pollinator network, including the PEF, was formed in 2010. During the first year of study, more than 3,500 bees were collected from these sites; future work will track changes in populations and relate them to local climate data.[8]

The PEF is also part of a regional study of long-term forest growth and yield across climatic and compositional gradients (Johnson 2012). This project involves a number of experimental forests and associated research sites in the Northeast and Lakes States. Response variables include stand-level growth and yield, i.e., stemwood volume and aboveground biomass accumulation and carbon storage. Researchers used a meta-analysis approach to compare variability within and between study sites in order to determine whether differences exist across the region. Climatic variables, such as minimum and maximum temperatures, growing degree days, and amount of precipitation, were assessed for their correlation to observed differences. Studies such as this one increase the relevance of experimental forest data by identifying and exploring the mechanisms for regional trends.

5.6 Conclusion

As we look to the future, it is essential that the Forest Service research on the PEF be continued. In the long-term silvicultural study, a comparison of productivity in even-and uneven-aged systems will not be possible until the even-aged stands reach rotation length, which will require another 30–40 years. The confidence associated with recommendations based on this research increases with each additional measurement cycle. The PEF research not only adds value to earlier studies but also serves as the basis for new studies on a wide range of emerging topics. It is our hope and expectation that Forest Service research in northern conifers will continue to evolve, and that Forest Service scientists and cooperators will continue to use the experimental forest to address critical science questions.

Acknowledgments We thank the many people who assisted us with our search for the historical information, images, and personal accounts presented in this chapter, particularly Robert Frank, Jr., Lawrence Safford, Frank Hagan, and Roger Collins (USDA Forest Service, retired); Michael Maguire, Peter McBride, Terry Miller, Mark Twery, Bill Leak, William McWilliams, B. Tyler Wilson, and Ralph Crawford (USDA Forest Service); Michael Rechlin (Principia College); Gould Hoyt (Paul Smith's College, deceased); Robert Seymour (University of Maine); and Eben Lehman (Forest History Society). Robert Frank, Jeremy Wilson (University of Maine), Susan

[8] Progress report on file at the U.S. Forest Service, Northern Research Station, Bradley, ME, USA.

Stout (USDA Forest Service), and an anonymous reviewer provided helpful reviews of an earlier version of this manuscript; this version was reviewed by Jeremy Wilson and Robert Seymour (University of Maine) and Thomas Schmidt (USDA Forest Service).

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