Chapter 9
Development of the Selection System in Northern Hardwood Forests of the Lake States: An 80-Year Silviculture Research Legacy

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Abstract The northern hardwood research program at the Dukes Experimental Forest in Michigan and Argonne Experimental Forest in Wisconsin has been adapting to changing management and social objectives for more than 80 years. In 1926, the first northern hardwood silviculture study was established in old-growth stands at the Dukes Experimental Forest. In response to social demands for more "natural" forestry, the study included then-contemporary practices (e.g., liquidation of old-growth forest) and new approaches (e.g., partial cuttings). By 1953, the partial cutting treatments were deemed most sustainable (Eyre and Zillgitt, Partial cuttings in northern hardwoods of the Lake States: twenty-year experimental results. Technical Bulletin LS-1076, 1953), and led to the creation of an uneven-aged stand structural guide that is still widely used today: the famed "Arbogast Guide" (Marking guides for northern hardwoods under the selection system. Station Paper 56, 1957). Charismatic figures such as Raphael Zon, Windy Eyre, William Zillgitt, and Carl Arbogast Jr. were important to establishing this research and its early application in the Lake States region. Since then, research at the Dukes and Argonne Experimental Forests has expanded to evaluate a range of management alternatives for northern hardwood forests, including approaches designed to sustain biodiversity, habitat, and timber production. In addition, the long-term studies provide new opportunities for larger-scale applications and research unforeseen at the studies' establishment. The lessons learned from the 80 years of research on northern hardwood ecosystems at the Dukes and Argonne Experimental Forests have led to numerous publications and management guides and have impacted thousands of forestry professionals and millions of hectares of land.

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9.1 Introduction

Forest managers face increasingly diverse and exciting land management challenges, including the call for socially acceptable and ecologically sustainable practices. Over the past few decades, the values that society has associated with forests have changed fundamentally. The previously dominant paradigm of economic growth, control of nature, and the view that natural resources were abundantly available has been replaced by one that focuses on sustainable development, harmony with nature, belief that the supply of natural resources is finite, and a strong emphasis on public involvement in land management decision making (Bengston 1994). Moreover, management of forestland used to be the domain of government agencies, forest product companies, and private landowners; now conservation organizations such as The Nature Conservancy are taking an active role in managing forestland. In addition, users of forestland are diverse in their characteristics and expectations and demand a broad range of high-quality recreational experiences. At the same time, managers are facing an expanding range of threats (e.g., climate change, nonnative insects and diseases, and landscape fragmentation) that endanger the ecological integrity of forests. This uncertainty has heightened the need for creative, innovative silvicultural prescriptions to increase forest heterogeneity and complexity (Coates and Burton 1997; Lindenmayer et al. 2006; Puettmann et al. 2009), and to help insure the long-term sustainability of forested ecosystems and the goods and services they provide. Addressing today's challenges in forest management requires both basic and applied research, short- and long-term perspectives, and insight into ways to apply findings at both small and large spatial scales. The amount of knowledge needed to address current challenges appears daunting, but long-term research on USDA Forest Service experimental forests (EFs) already provides some of that information.

The EFs were established to study problems at scales ranging from individual trees to forest stands, forests, and watersheds. These forests are outdoor laboratories where scientists observe natural phenomena and test hypotheses about ecosystem functioning. They enable scientists to test stand-level silvicultural practices and examine tree-level processes. Today, the EFs are incorporated into national networks to address basic and applied watershed- and landscape-scale questions.

In 1926, the then cutting-edge research on uneven-age silviculture, an alternative to high-grading and exploitive cutting in the region, was established by the Lake States Forest Experiment Station (LSFES, now part of the USDA Forest Service, Northern Research Station) on the Dukes (also known as Upper Peninsula) EF. This experiment, designed to sustain timber yield by increasing diversity in tree age and size, triggered eight decades of research that expanded over time to include basic and applied science questions. Research results have been applied across large regions and diverse forest types.

Fig. 9.1 Experimental Forests of the USDA Forest Service, Northern Research Station

9.1.1 The Dukes and Argonne EFs

This chapter focuses on the Dukes and Argonne EFs and the long-term uneven-age silviculture studies conducted on them. Research began on the Dukes EF in 1923 on a half section (142 ha) of land donated by Cleveland Cliffs, Inc., about 30 km southeast of Marquette, Michigan (Fig. 9.1). In 1938, the Dukes EF was officially established and incorporated into the Hiawatha National Forest; it has since expanded to 2,225 ha. A small amount of eastern white pine (*Pinus strobus* L.) and American elm (*Ulmus americana* L.) was logged in the early 1900s but the EF areas discussed in this chapter were otherwise considered old-growth northern hardwoods before research began (Adams et al. 2008). The 2,656-ha Argonne EF was established in 1947 and is located 200 km southwest of Dukes within the Chequamegon-Nicolet National Forest in northeast Wisconsin (Fig. 9.1). When silvicultural research at the Argonne EF began around 1950, the areas discussed in this chapter were second-growth northern hardwoods (Adams et al. 2008). The study stands had been commercial, clearcut, and were dominated by trees that established about half a century earlier, but also contained a component of older residuals (Erdmann and Oberg 1973). The site and stand differences between the Dukes and Argonne EFs provided opportunities to include more of the conditions encountered by managers in the region, and to expand and replicate research on northern hardwood silviculture.

9.1.2 The Lake States Northern Hardwood Forest

By the late 1890s and early 1900s, the white pine forests of northern Michigan and Wisconsin had been cut over, and many timber operators sold their holdings and moved west to California, Oregon, and Washington or south to Texas and Louisiana (Stearns 1997). Some of the larger operators in the Lake States, however, were familiar with the region's hardwood resources. They bought more land and converted old mills or built new ones to take advantage of this resource. In contrast to the pine forests of the region, the hardwood forests contained many different hardwood species that grew together, each with its own attributes and uses.

At the turn of the last century, northern hardwood forests were predominantly late successional in composition and structure (Frelich and Lorimer 1991). Shade-tolerant to mid-tolerant species, including eastern hemlock (*Tsuga canadensis* L.), American beech (*Fagus grandifolia* Ehrh.), sugar maple (*Acer saccharum* Marsh.), and yellow birch (*Betula alleghaniensis* Britton) dominated stands. Shade-intolerant species such as aspen (*Populus* spp.) were rare (Canham and Loucks 1984; Frothingham 1915; Stearns 1949). The forests were multi-aged with both very old and young trees growing together. This variety of age classes was the result of varying intensities of wind, the primary disturbance agent for this forest type. Frequent, low-intensity wind events result in small canopy gaps that support small saplings of shade-tolerant species (e.g., sugar maple, the dominant species in this forest type) within a stand of large trees. Rare, large-scale wind events maintain complexity at the forest scale and provide opportunities for less shade-tolerant species to establish (Frelich 2002; Hanson and Lorimer 2007).

9.1.3 A Need for Silvicultural Research

In the early twentieth century, some companies in the Lake States were experimenting with partial cutting, and, to facilitate regeneration, started tree nurseries. Many questions arose regarding the management and use of hardwood forests, and several companies hired professional foresters to manage their lands. In addition, the number of tax-delinquent land holdings grew in the 1920s, resulting in the establishment of county forests, state reserves, and national forests throughout the region. Much of this land had been cut over and presented significant management challenges, raising the need for more and better information to manage these public lands.

With this social context, the LSFES was established in 1923 to address problems of reforestation, forest fires, and local economy. By 1926, the Station had initiated partial-cutting studies on the Dukes EF, beginning an 80-year research legacy in uneven-age silviculture that expanded to the Argonne EF and across the northern hardwood range. In particular, the single-tree selection method has been studied extensively at the Dukes and Argonne EFs (Erdmann 1986; Godman and Books 1971; Strong et al. 1995). Though even-age silvicultural systems have also been studied at both EFs with successful results (Godman and Tubbs 1973; Tubbs 1977) and a research natural area at Dukes EF adjacent to the silvicultural research has provided stand dynamics information (Woods 2004, 2000), this chapter focuses on the uneven-aged silviculture research. The studies and staff at the Dukes and Argonne EFs were key in developing these systems, which were unknown and untested in the USA in the early twentieth century. Research results and applications from the

Dukes and Argonne EFs have crossed state and national borders, generated new areas of research, and influenced forest management throughout the region. The long-term silviculture studies also provide a platform for addressing current challenges that were not anticipated at the initiation of the early research program.

9.2 Beginnings of the Selection Paradigm at the Dukes EF (1920s–1950s)

The “Arbogast Guide,” a structural guide for an uneven-age silvicultural system called single-tree selection, is one of the most influential products of research at the Dukes EF. The Arbogast Guide was developed during the Selective Cutting Era (1925–1960), an early stage of development in the profession of American forestry (Seymour 2004). The forestry profession was focusing on sustained yield, a concept developed in Europe (the origin of most US silviculture). The sustained yield concept suggested that a negative exponential diameter distribution would result in sustained timber yield at the forest level (de Liocourt 1989). Meyer (1952, 1943) recommended negative exponential diameter distributions (q-structures, mathematically derived structures in which the ratios between numbers of trees in successive diameter classes are constant) for single-tree selection in the USA, thus applying the sustained yield concept at the stand level. At the time, the discipline of ecology was in its infancy and Clements’ (1916) theories on stable-state climax forests, where disturbances were viewed as unnatural, were shaping public opinions on forest management. Most people strongly opposed clearcutting and pressed for “near natural” forestry practices. In response to this cultural paradigm, newly formed USDA Forest Service Experiment Stations began research on uneven-aged silvicultural systems, viewed as more “natural” than even-age cutting practices. “Partial cutting” experiments were installed nationwide (Seymour 2004).

A Partial Cutting Study was installed at the Dukes EF in 1926. It consisted of eight experimental cutting treatments of varying intensities: reserve (uncut), diameter-limit cutting, light and heavy improvement cutting, overmature and defective (OMD) cutting, and clearcutting. The objective of the study was to devise a method of partial cutting that would prolong utilization of old-growth northern hardwood resources while gradually converting them into managed forests. This approach would sustain existing mature forests and support local economies until second-growth forests reached merchantable size (Eyre and Zillgitt 1950).

The first LSFES Station Director (1923–1944), Raphael Zon, designed the Partial Cutting Study. Zon was a charismatic figure in American forestry. He was a Russian immigrant who studied under Bernhard Fernow at Cornell University. His leadership resulted in the establishment of the USDA Forest Service research branch and the Journal of Forestry, the first professional periodical in American forestry (Ross 2008). Zon had keen interest in the selection system as an alternative to exploitive logging, an interest that was evident in the design of the Partial Cutting Study. As a strong proponent of the selection system, his aggressive promotion of

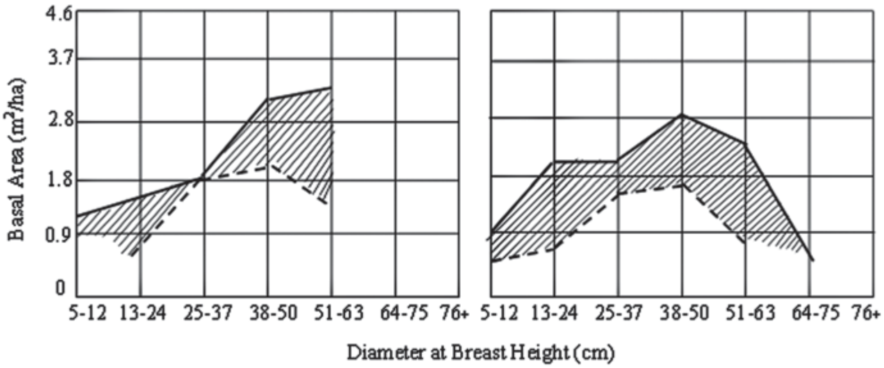

Fig. 9.2 Basal area after harvest, basal area 20 years later, and resulting cutting cycle growth in the overmature and defective No. 2 (*right*) and No. 1 (*left*) treatments. (Eyre and Zillgitt 1953)

this concept made him an important figure in the uneven-age silviculture legacy at the Dukes and Argonne EFs.

After the first 20 years of observation in the Partial Cutting Study, silviculturists F.H. "Windy" Eyre and William M. Zillgitt developed a monograph that explored the ecology, management, and special concerns of northern hardwood forests; it included the first structural guide for northern hardwood silviculture in the USA (Eyre and Zillgitt 1953). Carl Arbogast Jr., silviculturist, later presented this guide as a field forester's technical publication. Consequently, the structure that Eyre and Zillgitt (1953) originally proposed is better known today as the Arbogast Guide (1957).

9.2.1 Early Results, an Empirically Derived Structure

Arbogast (1957) recommended creating and maintaining uneven-aged stands with the empirically derived, reverse-J diameter distribution and residual stocking suggested by Eyre and Zillgitt (1953). Silviculturists observed this distribution, which was based on the OMD treatments of the Partial Cutting Study at the Dukes EF, to provide good growth (Fig. 9.2), continuous ingrowth, and adequate seedling reproduction. The OMD treatments removed all OMD trees regardless of the diameter (Eyre and Zillgitt 1953). Because residual stand growth could be harvested periodically without depleting the base structure, stands with the Arbogast structure (1957) were believed to provide stand-level sustained yield. Eyre and Zillgitt (1950) judged that the distribution of diameter classes "improved upon nature" by bringing in more size classes and more closely emulating a reverse-J distribution than the uncut, reserve treatment. In practice, structural changes are monitored and diameter classes with a surplus of trees are reduced to the recommended level of stocking at regular cutting cycles. In addition, mature trees are removed to regenerate new trees in their place. In balanced stands, the goal is to harvest only the growth gained in a cutting cycle without compromising the base structure of the stand (Arbogast 1957; Eyre and Zillgitt 1953, 1950; Meyer 1952; O'Hara 2002).

9.2.2 Acceptance and Application of Single-Tree Selection

An early emphasis on outreach and training by LSFES silviculturists working on the Dukes EF facilitated acceptance and application of the selection system as developed by Eyre and Zillgitt (1953). Raphael Zon promoted publication of early findings in the form of one-page "notes" as well as journal articles explaining detailed results, to get research information into the hands of practitioners and other user groups. His assistant director, Windy Eyre, encouraged outreach and training to share results with forest administrators even before data were published (Rudolf 1985).

This outreach and publication of early results from the Partial Cutting Study at the Dukes EF led to widespread adoption of single-tree selection in the Lake States. Memos in Station archives indicate that major landowners were already starting to apply the selection system instead of clearcutting by the mid-1930s. The regional forester required national forests in the Lake States to use single-tree selection in northern hardwood forests, and the Menominee Indian Reservation adopted selection-marking guides based on results from the Partial Cutting Study. Moreover, many large, private landowners, such as Goodman Lumber in northern Wisconsin and American Can Co. and US Steel in the Upper Peninsula of Michigan, began to use single-tree selection in northern hardwoods instead of clearcutting practices. This widespread application of research results is an excellent example of the successful outreach and training that affected agency and company policies and management of the region's forests.

9.3 Refinement of Single-Tree Selection (1950s–1990s)

During the 1950s, forestry began moving into the Production Forestry Era (1960–1990); research and management emphasized high forest productivity to meet post-World War II economic demands and forecasts of timber scarcity. Even-age silviculture became popular again for many forest types, and practices started to follow agricultural paradigms, including intensive site preparation, vegetation control, and thinning (Seymour 2004). In the northern hardwoods of the Lake States, USDA Forest Service research had always conducted both even- and uneven-aged silvicultural research. Even-age methods were shown to be feasible and productive for the northern hardwood forest (e.g., Godman and Tubbs 1973), unlike the turn-of-the-century exploitive cuttings. However, the success of the selection system and strong support for it by Station leadership and Station silviculturist Carl Arbogast Jr. resulted in its continued importance in the Lake States during the Production Forestry Era.

9.3.1 Results at Dukes

The unreplicated Partial Cutting Study motivated scientists to pursue replicated research at both the Dukes and Argonne EFs, especially with Joseph Stoeckler, Ph.D., trained in experimental design and statistics, on board. At the Dukes EF, a replicated Stocking and Cutting Cycle Study was installed in 1951 to test Eyre and Zillgitt's (1953) findings. The design was created by Stoeckeler, a strong proponent of replication, and Arbogast, a strong advocate for single-tree selection. The blocked design included different levels of stocking and different cutting cycles. After 20 years, the results supported Eyre and Zillgitt's (1953) recommendations of 16-m^2/ha residual sawlog stocking (3.5 m^2/ha in poles) and a cutting cycle of about 10 years, with growth rates around 0.5 m^2/ha after single-tree selection cutting. The recommended stocking was a result of high residual tree growth and low mortality. Because differences in net growth were negligible between cutting cycles of different lengths, practical considerations were recommended to guide management decisions about cutting cycle lengths (Crow et al. 1981). This replicated study provided robust, empirical evidence for using the selection system in northern hardwoods.

Single-tree selection increased the dominance of shade-tolerant sugar maple in long-term studies at the Dukes and Argonne EFs (Eyre and Zillgitt 1953; Metzger and Tubbs 1971); this led to the development of special cutting practices for mid-tolerant species. In even-aged stands, shelterwood cutting with release and thinning were effective for regenerating less shade-tolerant species and increasing tree species richness (Erdmann 1986; Erdmann and Peterson 1971; Godman and Tubbs 1973; Metzger and Tubbs 1971). In uneven-aged stands, experiments on the Dukes EF demonstrated that group openings (0.04 ha) near seed trees, with scarification, successfully regenerated yellow birch. Consequently, when appropriate, adding some group-selection openings to single-tree selection stands was recommended, to accelerate recruitment and increase tree species richness (Eyre and Zillgitt 1953; Arbogast 1957; Erdmann 1986).

Before the end of the Production Era, research activity at the Dukes EF, including the Partial Cutting Study and the Stocking and Cutting Cycle Study, ceased (temporarily) in 1981 when the field office in Marquette, MI, was closed and site administration was transferred to the Station's laboratory in Grand Rapids, MN (Adams et al. 2008; unpublished memoranda on file with the USDA Forest Service, Grand Rapids, MN). A letter from the deputy station director to the chief of the Forest Service in 1985 stated that some study areas on the Dukes EF were converted to demonstration areas for professional training and public education purposes.

9.3.2 Results at Argonne

When research started at the Dukes EF in 1926, one third of the forests on the Upper Peninsula of Michigan were still old growth; research focused on sustaining that resource base. By the 1950s, however, the Lake States landscape had changed and most forests were cutover. Yet, silvicultural systems for the second-growth northern hardwoods of the Lake States were still largely untested in 1950. As a consequence, the Station started to focus northern hardwood silvicultural research on second-growth forests at the Argonne EF.

A "Cutting Methods" study designed by Stoeckeler and Arbogast was installed on the Argonne EF in 1951, and included replicated even- and uneven-age treatments. The even-age results highlighted the effectiveness of the shelterwood method for northern hardwood regeneration (Godman and Tubbs 1973) and the value of crop-tree release to stimulate growth and quality development (Erdmann 1986; Erdmann and Oberg 1973). Research showed that tree quality could be increased by controlling tree density to reduce main stem forking and epicormic branching, which tend to degrade sawlog quality (Godman 1992). The work on uneven-age silviculture evaluated applicability of the diameter distribution devised by Eyre and Zillgitt (1953) to second-growth forests. Results from the selection cuts showed that higher residual basal areas (20.7 m^2/ha) increased stand quality (Godman and Books 1971), while lower residual basal areas increased growth (13.8 m^2/ha). The intermediate residual basal area, 17.3 m^2/ha, provided the best balance between stimulating growth and developing quality, which are both important considerations in managing northern hardwoods (Erdmann and Oberg 1973).

With most of the landscape in second-growth forests, a second important outcome from the Argonne EF research was the development of guidelines for conversion of even- to uneven-aged structures. Findings suggested that the first selection cuts in cutover stands could be heavier than previously thought; early annual growth of dominant and codominant trees did not differ between residual basal areas in the Cutting Methods Study. The heavier cuts increased early returns and extended the time until the next entry to 20 years. In addition, Arbogast (1957) had hypothesized that during conversion, pole-sized stands could be cut back to 20 m^2/ha, but experiments at the Argonne EF showed that this level of reduction was not economical. Finally, the second-growth stands had irregular diameter distributions, with few trees in the large diameter classes. Crop-tree release was found to accelerate growth into larger size classes in early harvests, and helped to hasten the development of reverse-J diameter distributions during conversion to an uneven-aged structure (Erdmann and Oberg 1973). The studies at the Argonne EF were maintained through the Production Era.

9.3.3 Outreach Traditions Continued

During the Production Forestry Era, the early emphasis on outreach and training at the Dukes EF was extended to the Argonne EF, where research focused on regional issues of managing second-growth northern hardwoods. Moreover, industry was interested in better utilization of second-growth forests and the work at Argonne addressed this need. At this time, the North Central Forest Experiment Station (formerly, the LSFES) began developing user-friendly management guides for major forest types. The first of these guides since the Arbogast Guide (1957) was for northern hardwoods (Tubbs 1977), and dealt with both even- and uneven-age management options and special issues associated with second-growth forests.

In addition to a new management guide, Richard (Dick) Godman developed a user-friendly series called the "Northern Hardwood Notes" (Godman 1992). The series was presented as a Station-published three-ring binder with one-page summaries of silvicultural systems for northern hardwoods, stand dynamics, regeneration, economics, and wildlife. The Notes could be augmented with additional pages as new information became available. Godman was an influential mentor to other Station scientists and a strong advocate for outreach. Though not trained in graduate school, Godman was knowledgeable about forest stand dynamics and the silviculture of northern hardwood forests. He was gifted in communicating technical information in terms that were meaningful to managers, foresters, and the public. He devoted his work time to outreach in order to get information into practitioners' hands rather than publishing journal articles for the scientific community. The regional forestry network respected him highly. The scientists working at the Argonne EF also disseminated information via field tours. Carl Arbogast Jr. continued outreach and tours about the single-tree selection system at the Dukes and Argonne EFs. In his opinion, single-tree selection was the "only way" to manage northern hardwoods and other options, such as even-aged systems, were not productive. He was known for expressing his opinions and highlighting his ideas in his tours. Silviculturists Dick Godman and Gayne (Gus) Erdmann designed a marking course to be incorporated into Argonne EF tours. The course trained field foresters in single-tree selection as well as even-age marking practices such as shelterwood cuttings, thinnings, and crop-tree release in second-growth northern hardwoods. Training sessions began in the 1970s and continue today. Virtually all forest management agencies in the Lake States have personnel trained at the Argonne and Dukes EFs, and thousands of foresters, forestry students, loggers, and small woodland owners have been trained at or have toured the Dukes and Argonne EFs.

9.3.4 Widespread Application to the Land

The emphasis on outreach and training at the Dukes and Argonne EFs greatly increased the application of single-tree selection in the Lake States and elsewhere, even though the Production Forestry Era emphasized even-age practices nationally. Major landowners within the Lake States based their silvicultural handbooks on the Dukes and Argonne EFs' study results. These landowners included state departments of natural resources (Wisconsin and Michigan), Wisconsin counties, Native American natural resource agencies (Menominee Tribal Enterprises, Lac Du Flambeau, Keweenaw Bay, and Bureau of Indian Affairs), large industrial landowners (American Can Co., Owens-Illinois, Keweenaw Land Co., Mead Paper Co., Champion International, Consolidated Papers, Inc.), national forests (Chequamegon-Nicolet, Ottawa, and Hiawatha), and even provincial lands (Quebec and Ontario). Estimates by Jacob (1987) suggest single-tree selection is the most widely used silvicultural system in the northern hardwood forests of the Lake States.

9.4 Tests of the Empirical Structure Outside the Lake States

Tests of the research results from the Dukes and Argonne EF experiments at other locations were important because northern hardwoods are found from the Lake States to the northeastern USA and eastern Canada. In Michigan and Wisconsin alone, more than 4 million ha are in northern hardwood forest (Jacobs 1987). Silvicultural research elsewhere in the forest type highlights the range of forest outcomes possible.

9.4.1 Lake States

The Ford Center, a property of Michigan Technological University, installed studies in its lower-quality sites and high-graded, second-growth northern hardwood stands to test the structure developed by Eyre and Zillgitt (1953) and recommended in the Arbogast Guide (1957). Eric A. Buordo designed the study in consultation with Carl Arbogast and used selection treatments similar to those at the Dukes and Argonne EFs. Although the study treatments are not replicated, the study has been maintained for more than 50 years and is unique because the cuttings were initiated when the stands were at low stocking levels relative to recommendations by Arbogast (1957). One study at the Ford Center showed that after 40 years of single-tree selection cutting, stand structure varied and only one of five stands had a reverse-J diameter distribution (Neuendorff et al. 2007). Another study at the Ford Center and in the surrounding region demonstrated that commonly practiced uneven-age methods, which do not adhere to strict stocking guides, resulted in compositional and structural variability similar to that observed in selection stands (Schwartz et al. 2005). The recent research at the Ford Center illustrates the variability of individual stands, and the possibility that applying the same treatment to other locations might not result in the anticipated outcomes.

Economic modeling was used to compare alternative diameter distributions to the Arbogast empirical structure. Analyzing data from northern hardwood forests of central Wisconsin, Adams and Ek (1974) showed that more volume in smaller size classes resulted in higher economic gain. This study was one of the first of many to use modeling to test the empirical structure derived at the Dukes EF.

9.4.2 Northeastern States

Long-term studies of selection cutting in northern hardwood forests in the Northeast included similar experiments. Unlike the work at the Ford Center, they did not involve collaboration with silviculturists working on the Dukes or Argonne EFs. In general, studies of the selection system in the northeastern USA have shorter temporal records and little or no replication.

Table 9.1 Basal area distribution of two independent, empirical stand structures for northern hardwood forests by diameter at breast height (dbh) class

	Bartlett EF[a]	Dukes EF[b]
Dbh (cm)	Basal area (m^2/ha)	Basal area (m^2/ha)
15–30	4.6	4.8
30–45	6.4	6.7
45 +	7.3	7.3

[a] Gilbert and Jensen (1958), Leak et al. (1969, 1987)
[b] Eyre and Zillgitt (1953), Arbogast (1957)

Gilbert and Jensen (1958) reported 25-year results from a trial of single-tree selection cutting in northern hardwoods on the Bartlett EF in New Hampshire. Findings were later updated by Leak et al. (1987, 1969). Though developed independently of research at the Dukes EF, this empirically derived structure has a similar size class distribution to that of its counterpart in Michigan (Nyland 2002; Table 9.1).

Additional trials of selection cutting explicitly using the structure and guidelines suggested by Eyre and Zillgitt (1953) and Arbogast (1957) were initiated in the 1970s and 1980s in New York (Mader and Nyland 1984; Nyland 1987). Stand structures have remained stable and growth rates (Nyland 2002) have been similar to those observed on the Dukes (Eyre and Zillgitt 1953) and Bartlett EFs (Leak et al. 1969). Hansen and Nyland (1987) also used computer simulation to test Eyre and Zillgitt's (1953) suggestion that a lower residual basal area and longer (15- to 20-year) cutting cycle could be maintained over a 30-year period (Nyland 2002). Growth rates were comparable if managers matched the residual density with an appropriate cutting cycle (Hansen and Nyland 1987). Nyland (2002, 1998, 1987) has recommended the Arbogast (1957) guidelines for selection system silviculture of northern hardwoods in the Northeast.

Studies of the selection system in the Northeast highlighted the dominance of shade-tolerant species in the regeneration (Seymour 1995). American beech, an economically low-value species because of the widespread effects of the beech bark disease (a complex between the scale insect *Cryptococcus fagisuga* and fungi of the genus *Nectria*), was favored by single-tree selection cutting (Leak and Wilson 1958). Group (or patch) selection was shown to be more effective for recruitment of mid-tolerant species such as yellow birch (Leak 2005; Leak and Wilson 1958; Nyland 1998).

9.4.3 Eastern Canada

Long-term studies of the selection system started in Quebec in the late 1980s. Diameter-limit cutting had commonly been used to remove high-value species. The selection system was regarded as the best silvicultural option to restore stand structure and sustain yield of high-quality products (Bedard and Huot 2006). In 1987, the first long-term study of the selection system was installed to test a theoretical *q*-structure and compare findings with empirical structures of Eyre and Zillgitt (1953), Crow et al. (1981), and other researchers. Ten years after cutting, net annual growth rates were similar to those reported by Crow et al. (1981) and Eyre and Zillgitt (1953). In addition, residual densities of 16.8–21.2 m^2/ha (similar to Eyre and Zillgitt 1953) were effective at increasing numbers of sugar maple and yellow birch saplings (Bedard and Majcen 2001).

9.5 Criticisms and Alternatives to the Empirical Structure

Even though single-tree selection using the target diameter distribution suggested by Arbogast (1957) has been widely applied, the system has had its critics. Criticisms of the Arbogast Guide and other theoretically balanced stand structures come from the profession of forestry and discipline of ecology. The Arbogast Guide assumes that stand-level sustained yield is both necessary and attainable and its complexity has created some "obsession" to impose the structure without considering the ecological applicability of doing so (Guldin 1991; O'Hara 2002). This type of application appears to be in contrast to a tenet of silviculture, which is expressed in one textbook as follows: "The practice of silviculture does not consist of rigid adherence to any set of simple or detailed rules of procedure" (Smith et al. 1997, p. 17). The idea of balanced uneven-aged distributions was based on observations at the forest level in Europe, not at the stand level (de Liocourt 1898), which contributes to the problem of attaining stand-level sustained yield. Even today, in European forests, where silviculture has been practiced for centuries, selection systems are still evolving to address sustainability (O'Hara et al. 2007) and sustained yield at the stand level remains an idyllic concept (Smith et al. 1997).

Selection cuttings manipulate diameter distributions under the assumption that size is a surrogate for age; in other words, balanced size structures are balanced age structures. Yet studies of tree age–size relationships have revealed that diameter is not equivalent to age, particularly for shade-tolerant species (e.g.,Seymour and Kenefic 1998). In fact, mixed-species and even-aged stands may develop a diameter distribution similar to the reverse J, due to crown class differentiation within a single age class, or stratification among species (Oliver and Larson 1996; Smith et al. 1997). This pattern of development will influence the outcomes of silvicultural treatments because trees in lower crown classes or of slower-growing species may not respond to release as expected.

The single-tree selection system has no specific provision for regeneration aside from residual stand basal area. Seedlings of desirable species are assumed to establish and recruit in a timely manner if stand-level stocking is controlled. In practice, insufficient regeneration or regeneration of undesirable species (e.g., beech) may occur (e.g., Donoso and Nyland 2006), or seedlings and saplings may experience slow growth and competition-induced mortality.

Studies of old-growth forests show that diameter distributions other than reverse-J shapes are common and could be used as guides for management (Frelich and Lorimer 1991; Janowiak et al. 2010; Leak 1964; Tyrrell and Crow 1994). For instance, the rotated sigmoid distribution has been observed in old-growth northern hardwoods, and may be a more realistic model for managed stands. A rotated sigmoid distribution reflects high mortality of small-diameter trees from self-thinning, vigorous growth, and low mortality in the middle size classes, and increased mortality due to senescence in the largest size classes (Goff and West 1975). Past work on the Argonne and Dukes EFs has focused on reverse-J diameter distributions.

Silvicultural systems may not duplicate the effects of natural disturbance. The single-tree selection system, originally perceived as more "natural" (O'Hara 2002), does not in reality emulate the complete natural disturbance regimes of northern hardwood forests. Frequent light harvests perpetuate sugar maple, reduce tree species richness (Neuendorff et al. 2007; Strong et al. 1995), and do not emulate intermediate-intensity wind events. Intermediate disturbances, such as thunderstorm downbursts, remove 10–50% of the overstory trees in localized stands and tend to occur at least once over the life span of a cohort of trees (Frelich and Lorimer 1991; Hanson and Lorimer 2007; Seymour et al. 2002). Patchiness in regeneration perpetuates mid-tolerant species and creates irregularly uneven-aged rather than "balanced" stands (Frelich and Lorimer 1991; Woods 2004).

Because the balanced reverse-J structures have received criticism from both inside and outside of the profession of forestry, alternative methods for uneven-aged silviculture have been proposed. Beginning in the 1970s, alternative structures were suggested for different management objectives (e.g., Leak and Gottsacker 1985), economic factors (e.g., Buongiorno and Michie 1980), and optimization of production (e.g., Adams and Ek 1974). More recently, research has focused on group selection as an option to maintain mid-tolerant species in uneven-aged stands (Leak 1999; Shields et al. 2007; Webster and Lorimer 2005, 2002). In addition, multicohort approaches, which use area control to create spatially distinct cohorts, have been recommended (Lorimer and Frelich 1994; O'Hara 1998; Seymour and Hunter 1999). These approaches have been suggested for maintaining landscape patches of mid-tolerant seed sources, creating heterogeneity in the landscape for habitat, and more closely mimicking intermediate disturbance events (Hanson and Lorimer 2007). Furthermore, newer concepts highlight techniques to support ecological function in managed stands by increasing large woody debris, maintaining decadent trees, creating microtography, designating permanent no-cut areas, and extending cutting cycles (Franklin et al. 2007).

9.6 Maintenance of Legacy Studies and New Directions (1990s–present)

As societal values related to environmental management began to shift in the later part of the twentieth century, forestry began experiencing a corresponding shift to a new resource management paradigm (Bengston 1994). The old "multiple-use sustained-yield" forest management model had guided management for decades; the sustained-yield philosophy can be traced back to eighteenth- and nineteenth-century central European traditions of forest management. By the late 1990s, forestry began to embrace the concept of ecological forestry (Seymour and Hunter 1999), a concept that also influenced work on the Dukes and Argonne EFs. The Ecological Forestry Era (1990–present) entails a landscape triad approach, where production forests and ecological reserves are embedded in a forest matrix managed for a broad range of ecosystem goods and services. Ecological forestry uses natural variability in structure and composition as a way to manage for most species in a forest, a coarse filter approach in biodiversity conservation (Seymour et al. 2007). With the profession focusing on more than just production of wood in the 1990s, the silvicultural research vision at the Dukes and Argonne EFs expanded to include ecological forestry, while still maintaining much of the legacy work of previous eras.

During the Ecological Forestry Era, Terry Strong, silviculturist, maintained the Cutting Methods Study, along with several other studies at the Argonne EF. His primary emphasis was on outreach with more than 1,800 people trained from 20 different organizations between 1993 and 2003. He also helped to integrate Station silviculture research results into new editions of silvicultural handbooks for state, federal, tribal, and industrial landowners, many of whom were already applying selection practices. In addition, some new research was added on the effects of management on a wider array of ecosystem goods and services. For example, the Cutting Methods Study at the Argonne EF was used to compare economic and tree diversity responses among the study's treatments. Long-term data (40 years) showed that heavy to medium single-tree selection was more economical and provided the benefit of higher regeneration diversity than diameter-limit cutting, which initially appeared more economical (Niese and Strong 1992).

9.6.1 Visions for the Future at the Dukes and Argonne EFs

With the full support of Station leadership, research activity at the Dukes EF was revitalized in 2002 when new silviculture project leader Brian Palik reopened the Stocking and Cutting Cycle Study. Palik saw value in extending the existing long-term databases and recognized that analysis of data from historical experiments could offer insights into forest sustainability. Reinvigorating research at Dukes EF also offered opportunities to look at old work, at Dukes and Argonne EFs, in new ways. Under Palik's direction, permanent plots were remeasured and harvests were scheduled to reapply the original treatments at the Dukes and Argonne EFs. In addition, several new projects were started at both EFs, reflecting three new visions: (1) maintenance of long-term studies for their original purposes, (2) new research and unforeseen opportunities, and (3) increasing the scale of inference for various studies.

9.6.2 *Vision 1: Maintenance of Long-Term Studies for Their Original Purposes*

9.6.2.1 More than 80 Years of Balanced Stand Structure Research

With renewed interest in the historical experiments at the Dukes EF, Palik scheduled the original Partial Cutting Study established in 1926 to be re-treated following the original study plan. The study had been periodically measured until 1966 and had been treated by the Hiawatha National Forest for demonstration purposes in 1985. No analysis of long-term findings had been published since Eyre and Zillgitt's (1953) monograph, even though the Arbogast Guide (1957) remains the most widely used structural goal in uneven-age northern hardwood silviculture. In 2007, a remeasurement of the study provided an 80-year record which scientists can use to support or challenge the predictions by Eyre in Zillgitt (1953) and evaluate the sustainability of their empirical structure.

9.6.2.2 Stand Structure in Managed Old Forests

While the Stocking Levels and Cutting Cycles Study was conceived with other objectives in mind (Crow et al. 1981), this study presented an opportunity to examine tree quality and structural characteristics after more than 50 years of selection system silviculture. Extending rotation ages in even-aged stands or growing and maintaining older cohorts of trees in uneven-aged stands is of increasing interest in many different forest types (Curtis 1997; North and Keeton 2008). One rationale for retaining older trees is that such stands will contain more of the structural characteristics of old-growth stands such as large-diameter trees with deeply fissured bark and large crowns, snags, and large deadwood on the ground that are important to some plant and animal species. Empirical data on tree growth and stand structure from long-term experiments are needed to inform managers about what to expect when managing for older tree ages. Structural data indicate that snag density is not greatly affected by cutting cycle (5, 10, or 15 years), but does vary widely by stocking level (Gronewold et al. 2010). Density of large snags (>30-cm dbh) is consistently higher at high stocking levels (20.7 m^2/ha), regardless of cutting cycle, and these densities are similar to unmanaged old growth. Additionally, density of small snags (<30-cm dbh) is higher at lower stocking levels (Gronewold et al. 2010). The work emphasizes the flexibility that managers have in using different selection system options to address the management concerns of the Ecological Forestry Era.

9.6.2.3 Informing Simulation Models Using Data from Long-Term Studies

Empirical data from long-term studies are invaluable for answering questions about management effects on forests. Recent advances in computer modeling provide an additional avenue for addressing these questions. Yet these models are only as good as the data used to calibrate and verify them, and depend on long-term studies on EFs as a valuable source of that information. One such effort is the CANOPY model developed by Craig Lorimer and students at the University of Wisconsin (Choi et al. 2001). CANOPY can simulate a wide variety of treatments in northern hardwood stands over long time periods. It generates an array of response variables related to forest composition, diameter distributions, volume growth, and large deadwood abundance. CANOPY was calibrated and verified using data sets from regional northern hardwood silvicultural studies, including long-term studies on the Dukes and Argonne EFs. It simply would not have been possible to bring the CANOPY model to its current level of accuracy and precision without use of the long-term data sets from the EF studies.

9.6.3 Vision 2: New Research and Unforeseen Opportunities

9.6.3.1 Incorporating Ecological Forestry

Managing forests to restore or sustain structural and compositional characteristics of old unmanaged stands has emerged as an issue of concern for northern hardwood ecosystems in the Ecological Forestry Era (Crow et al. 2002; Keeton 2006). The goal generally is not to create old-growth stands per se, but to create greater structural complexity and maintain older cohorts of trees within stands managed for wood products, perhaps with silvicultural approaches that better emulate natural canopy disturbances. Recent research in the Great Lakes region has found that mesoscale canopy disturbances that remove 30–60 % of the overstory basal area in a patchy distribution are fairly common and important for establishment of mid-tolerant species, and for creating multi-cohort age structure (Hanson and Lorimer 2007). A silvicultural analog for this disturbance regime is being tested operationally on the Argonne EF in collaboration with the Wisconsin Department of Natural Resources and the University of Wisconsin. The treatment consists of single-tree selection cutting with interspersed 0.8-ha shelterwood cuts and deliberately creating large deadwood (both snags and logs) to enhance wildlife habitat. The concept is rooted in basic philosophies of ecological forestry (Franklin et al. 2007) and supplements structural attributes missing in traditional single-tree selection system cutting. This work may suggest new empirical structures and alternate approaches for management to address needs of Ecological Forestry Era.

9.6.3.2 Simulation Modeling of Ecological Objectives in Northern Hardwood Management

Currently, the CANOPY model is used to ask questions about long-term effects of traditional management, as well as some newer approaches, on stand structure and composition. For example, simulations examine how long-term application of single-tree selection based on the Arbogast Guide influences the composition of mid-tolerant tree species and compares the predictions to outcomes from Menominee Tribal Forestry group selection cutting tailored to maintain these species. Another question is how permanent retention (for the life of the tree) of selected canopy trees influences wood volume production in stands managed with the selection system. This guideline is now being implemented on the Chequamegon-Nicolet National Forest (USDA Forest Service 2004) to enhance wildlife habitat and maintain sources of large deadwood.

9.6.3.3 Sustaining Productivity and Carbon Storage

The long-term data from the Dukes and Argonne EFs provide opportunities for addressing emerging science questions that could have not been foreseen when the studies were established. Responses to increased threats to forests and the impending changes, whether from climate, introduced pathogens and pests, or market demands, can be informed by long-term data on stand dynamics and response to different disturbances. The long-term research in the EFs provides this type of information, including detailed data on level of harvest or disturbance intensity. For example, recent work is examining how soil physical attributes affect ecosystem productivity varies across a gradient of cutting intensities over long-time periods at the Argonne EF and other EFs (Tarpey et al. 2008).

9.6.4 Vision 3: Increasing Scale of Inference for Various Studies

A third vision for the Dukes and Argonne EFs is to expand their scale of inference from stands to landscapes. Silvicultural and ecological research has generally moved to studies larger in scale than the small, stand-scale studies established on the Dukes and Argonne EFs. Understanding research results at larger scales provides context and applicability of the findings. Increasing scale entails both installation of operational-scale studies and creatively using already existing long-term study data at larger scales.

Operational-scale research, with treatment units similar in size to managed stands, provides realistic examples of innovative silvicultural systems and a training ground for managers. Large-scale treatments were initially used in silvicultural research in the 1920s. However, later study installations were small in scale because maintaining large-scale studies was expensive and replication was difficult within limited land bases for research use (Seymour et al. 2007). Today, new silvicultural studies are operational in scale, like the new ecological forestry study at the Argonne EF.

Recently, Forest Service research and development has encouraged and financially supported the development of an Experimental Forest and Range Network encompassing more than 80 EFs and Ranges across the USA. Other chapters in this book demonstrate that the research histories of many of these EFs have been long and similar to those of the Dukes and Argonne EFs. This support from the Washington office has led to unprecedented opportunities for EF managers to exchange ideas and findings with each other at national EF and Range workshops (e.g., Adams et al. 2010). One goal of this group is to link the long-term databases across EFs (Vavra and Mitchell 2010). The Dukes and Argonne EFs will contribute to this network, opening opportunities to address questions that could not be answered with individual EF databases. Research topics could range from basic silviculture to climate change.

9.7 Summary

The Dukes and Argonne EFs have rich research histories that have inspired unique research trajectories and widespread application of uneven-age management to the northern hardwood resource of the Lake States, northeastern USA, and eastern Canada. In response to social and professional needs in silviculture, innovative research on partial cuttings for sustaining old-growth forest resources was established early in the twentieth century and resulted in the empirically derived Arbogast Guide. The research, key staff, and extensive outreach influenced policy and management across the range of northern hardwood forest; they also helped to educate managers, students, and private landowners about appropriate methods for hardwood management. The Dukes and Argonne EFs research has transformed the northern hardwood landscape by informing managers and changing regional practices from exploitive cutting to more sustainable and socially acceptable practices. The Argonne and Dukes EFs also have served as sites for some of the longest replicated silvicultural research in the northern hardwood forest type. Today, these studies and databases offer opportunities to test long-term responses of forests to management and to address new questions unanticipated at the time of study establishment. The future of the Dukes and Argonne EFs includes maintenance of those long-term studies, addressing needs of the current Ecological Forestry Era, capitalizing on the long-term databases for emerging science needs, and expanding the scale of inference.

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