Chapter 7
Uneven-Aged Management After a Half-Century of Research on the Forest Service Fernow Experimental Forest in West Virginia

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Abstract Uneven-age management in forestry refers to a system of management that periodically selects individual trees or small groups of trees for harvest. In general, the concept of uneven-age management entails the sustained yield of forest products while maintaining continuous forest cover. In North America, interest in uneven-age management grew in the second half of the twentieth century after most of the old-growth forests had been harvested. In West Virginia, uneven-age management and its surrogates have been studied intensively since 1948 at the Forest Service Fernow Experimental Forest. The Fernow Experimental Forest is located in the Allegheny Mountains of the Central Appalachian Broadleaf Forest and has characteristics of both mixed-oak and northern hardwood forests, depending on site characteristics. In stands managed with the type of uneven-age management known as "single-tree selection," only those species capable of developing in reduced sunlight conditions have thrived. Concerns that the increased dominance of these so-called shade-tolerant species would lead to lower productivity have not been validated. It appears that managing the stocking level, or the size and number of trees after harvesting, has helped to sustain higher than expected levels of wood production and carbon storage. Economically, uneven-age-managed stands have produced periodic revenue that resulted in higher net present values than either clearcut or unharvested stands, and, unlike more exploitive procedures, did not deplete the residual stand value. Unexpected insights into forest ecology and management also were realized by carefully studying the response to treatments for more than a half century and the benefits of long-term forestry research are discussed.

Keywords Single · Tree selection · Diameter · Limit selection · Partial harvesting · Species diversity · Productivity · Mixed · Mesophytic · Long · Term forest research

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7.1 Introduction

7.1.1 Boom-and-Bust Era

Uneven-age forest management research on the Fernow Experimental Forest in West Virginia began after World War II. Initial interest in this form of management was in part a response to an earlier period of forest exploitation from about 1880 to 1920 that removed virtually all of the old-growth forests in the central Appalachian Mountains (Clarkson 1964). During this era, industrialists purchased vast tracts of land, or the timber rights to the land, and built mills that employed the newest technology capable of processing the timber from hectares of forestland each day. Temporary rail lines were constructed to reach the forests; and towns emerged or grew to provide the labor and services needed, leading to a generation-long economic boom in the region (Whitney 1994). For example, in Davis, WV, various mills processed roughly 2.4 million m^3 of timber during this period until the supply ran out (Clarkson 1964). Between the 1880s and 1920, harvesting proceeded across large tracts of land with little to no regard for any other resources. To make matters worse, wildfires of historic proportions often followed in cutover areas when sparks from steam-driven locomotives ignited the drying slash left behind after harvesting (Brose et al. 2001). Such fires burned with high intensity and degraded soils and water quality, destroyed valuable regeneration and wildlife habitat, and spread to adjacent uncut forests. As the timber supply ran out, rail lines were removed, mills were closed, unemployment jumped, and local populations declined. In some cases, small towns were depopulated entirely. In Tucker County, WV, where the Fernow Experimental Forest is now located, ten towns that existed during the timber boom era are gone today (Fansler 1962).

7.1.2 Early Twentieth-Century Forest Conservation Efforts

At the start of the twentieth century, the pattern of boom-and-bust forest exploitation in several regions and fears of looming timber shortages in the USA led to interest in forest conservation and the development of forestry as a science. The American Forestry Association and the National Academy of Science, supported by business interests, advocated for the federal purchase of forestlands in the eastern USA to serve as timber reserves (Robbins 1982). Eventually, the Weeks Act of 1911 authorized the federal purchase of private forestland in the eastern USA, which resulted in the establishment of the first eastern National Forests. Although the Weeks Act was controversial at the time, these new federal lands ultimately were created to protect the headwaters of navigable waterways and serve as examples of science-based forest management. Concurrently, the first forestry schools granting 4-year degrees were established in the USA to train the professionals needed to employ science-based forest management techniques. Concepts in these early forestry schools were taught by foresters trained in Europe such as Bernhard Fernow, a pioneer of professional forestry in North America and the founder of the first forestry schools to grant 4-year degrees in the USA and Canada (Rodgers 1991).

In Europe, forest management was already well established and professional foresters often managed estates for long-term objectives. Europeans had depended on their forests for centuries to supply many needs, including building materials, wood for fuel, and forage for livestock. Foresters in Europe often relied on partial harvesting and advanced the concept of uneven-age management, which involved removal of trees from all size classes to mimic the patterns of older, unmanaged forests (de Liocourt 1898). In theory, these stands would be kept at stocking levels (determined by the number and size of trees) low enough to allow for acceptable growth rates of existing trees and permit periodic harvests that could be sustained indefinitely. This theory was discussed in the USA early in the twentieth century (Graves 1910), and more fully articulated later in the century (Meyer 1943, 1952), when the social, political, and technological circumstances were more favorable.

7.1.3 The Fernow Experimental Forest and Late Twentieth-Century Forest Management

To establish the new Monongahela National Forest, as authorized by the Weeks Act, the first USDA Forest Service purchase of private land in West Virginia, referred to as the Arnold tract, occurred in 1915. In 1934, most of the Arnold tract became the 1,475-ha Fernow Experimental Forest (expanded to 1,900 ha in 1974) and was dedicated to forest research and forest management demonstration under the leadership of the Appalachian Forest Experiment Station. Roads, firebreaks, and a water reservoir were among the first projects on the Fernow and were built by the Civilian Conservation Corps in the 1930s. Research was just getting started in earnest when the national war effort forced the closing of operations in 1941. But in 1948, the facility was reopened under the administration of the Northeastern Forest Experiment Station (currently the Northern Research Station). The research mission at the time was focused on timber and watershed management (Trimble 1977). The Fernow was chosen as a research site because it is representative of the many ecological conditions found throughout the region, including those of the Allegheny Mountains of northern West Virginia, western Maryland, and central Pennsylvania, and to some extent those of the unglaciated Allegheny Plateau of western West Virginia, western Pennsylvania, and southwestern Ohio, and the Cumberland Mountains of eastern Kentucky.

At the beginning of the postwar era, Americans were still concerned about the exploitive harvesting practices seen earlier in the century. For example, when a Forest Service survey of forestlands across the USA was conducted in which harvest levels or “cutting practices” were evaluated as “excellent” to “poor” based on the amount of residual growing stock remaining after a harvest, “poor” was equated with the lowest levels (Harper and Rettie 1946). This terminology was further refined and implemented at the regional level and demonstrations of cutting practice levels (CPL) were established at several experimental forests throughout the region in the 1950s (Kenefic and Schuler 2008). In most cases, the "excellent" and "good" examples of forest management in these studies were implemented as uneven-age management using European-inspired forms of single-tree selection, which selects individual trees for harvesting and reserves others for continued growth. Poor management was most closely linked with heavier levels of removal, often implemented as a commercial clearcut without removal of trees with poor form or significant rot, usually referred to as cull trees (Weitzman 1949). Commercial clearcutting removes all trees of monetary value at one time and is similar to past exploitive practices, although on a smaller scale. In the 1950s, the lessons of the first half of the twentieth century were that exploitive harvesting, which looked similar to commercial clearcutting, compromised good forest stewardship and resulted in conditions that did not permit a sustainable flow of goods and services from the forest (Harper and Rettie 1946). By the postwar era, the capital-intensive logging that had occurred at the turn of the century in the Appalachians was no longer an option because virtually all of the forests had been exploitively logged just a few decades earlier. Many forest scientists and leaders in the field turned to uneven-age management as a possible alternative to foster better forest stewardship and enhance recovery of the region's cutover forests.

On the Fernow Experimental Forest, at least three early research initiatives addressed uneven-age management. One of the first studies was a variant of the regional CPL initiative that consisted of four treatments: two levels of uneven-age management implemented as single-tree selection, a diameter-limit cutting procedure, and a commercial clearcut harvest. In 1948, forest researchers designated these treatments as high-order, good, fair, and poor cutting practices, respectively. The commercial clearcut or poor cutting practice was considered the prevalent liquidation method of forest harvesting (Weitzman 1949). The CPL study was implemented as a small-scale case study and demonstration (10 ha, including the unmanaged reference area added in 1953).

A much larger experimental design involving three different site classes and three silvicultural practices, including uneven-age management, was started in 1950 on the Fernow as well. The larger study consisted of 21 physical research units, or compartments, on 280 ha. This study is referred to as the Large Area Comparison of Forest Management Practices, hereafter referred to as the LAMP study. The third prominent uneven-age type study was initiated in the 1970s and was designed to provide a silvicultural means for periodic partial harvests based on individual tree financial maturity and is referred to as financial maturity diameter-limit selection (FMDL; Trimble et al. 1974). The FMDL study was replicated on six research units or compartments on 97 ha. FMDL requires the removal of trees of poor vigor and quality as a first step and then provides guidelines for residual stocking based on financial maturity of individual trees and a desired financial rate of return.

Together, these three studies (CPL, LAMP, and FMDL) provide unparalleled insight into the ecological and economic qualities of uneven-age management in the central Appalachians after more than a half century of repeated harvests, forest responses, and continuous research and monitoring. These studies have been used by scientists to examine both ecological and management issues and have been the source of many scientific publications and management recommendations. The objective of this chapter is to provide an overview of these three studies and discuss some of the findings, management implications, and emerging issues related to using uneven-age forest management in the region today.

7.2 Fernow Experimental Forest

7.2.1 Characteristics and Layout

The Fernow Experimental Forest is located in the Allegheny Mountains of the Central Appalachian Broadleaf Forest, which forms the prominent uplift of the Appalachian Mountains in West Virginia. The Fernow is best characterized as a mixed-mesophytic forest type, which has characteristics of both mixed-oak and northern hardwood forests depending on aspect, elevation, and slope position (Braun 1950). The average growing season is 145 days (May–October) and the mean annual precipitation is about 142 cm, which is evenly distributed throughout the year (Pan et al. 1997). Growing-season temperatures are typically moderate and growing-season moisture deficits are uncommon (Leathers et al. 2000). The topography is mountainous and elevations range from 530 to 1,110 m above sea level. Common overstory species include northern red oak (*Quercus rubra*), sugar maple (*Acer saccharum*), and yellow-poplar (*Liriodendron tulipifera*) on the mesic sites, and chestnut oak (*Q. prinus*) and red maple (*A. rubrum*) emerging as dominants on the more xeric sites. Aspect and slope position are important determinants of site productivity and species composition. In all, more than 30 commercial species are found throughout the Experimental Forest (Madarish et al. 2002). Understory species composition is rich and often includes stinging nettle (*Laportea canadensis*), violets (*Viola* spp.), and several fern species; understory species vary with site and disturbance history (Gilliam et al. 1995).

The Elklick watershed (which later became the Fernow) was initially logged between 1903 and 1911 (Trimble 1977) during the railroad logging era (Fansler 1962). Horses and log slides were used to get harvested trees to the temporary rail lines. Trees close to the railroad were cut and used for a variety of purposes, including lower-value products such as mine timbers, but as distances and corresponding costs increased, the merchantability standards also increased. Some trees were left behind because their commercial values were less than the cost of removal. The landscape left behind had variable residual stocking and some older and larger trees with poor form or lower value.

At the beginning of the postwar era, the Fernow was compartmentalized into physical research units and small watersheds usually ranging in size from 10 to 30 ha. Sidney Weitzman was responsible for setting up the general research plan on the Experimental Forest, which emphasized silviculture research, large-scale demonstrations of various timber and watershed practices, and better understanding of

Fig. 7.1 Location of compartments on the Fernow Experimental Forest in West Virginia assigned to studies that incorporate uneven-age management concepts

the costs associated with a range of forest management options (Weitzman 1949). The research approach and some studies remain operative today and are a testament to the vision of Weitzman and his colleagues for setting up a plan that has persisted for more than 60 years. For example, the CPL, LAMP, and FMDL studies employ this approach and use 32 different compartments for various treatments, totaling nearly 400 ha (Fig. 7.1). By utilizing this approach, the research staff on the Fernow

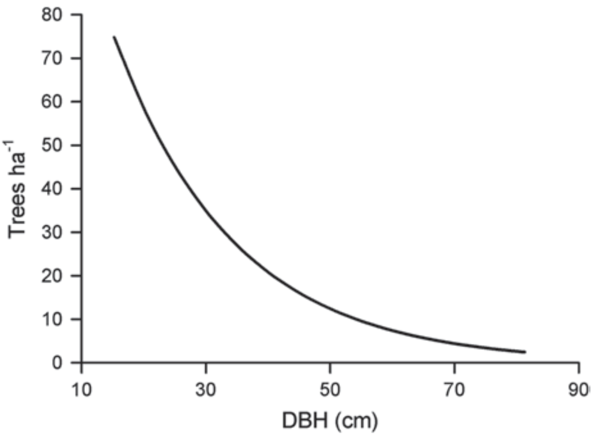


Fig. 7.2 Theoretical size-class distribution of an uneven-aged stand with a *Q* factor of 1.3

can examine the long-term consequences of managing forests in blocks of land that are large enough to be commercially operable, and typify the ownership size of private lands in the region. Moreover, long-term repetition of specific silvicultural treatments is critical when various forms of partial harvesting are being evaluated because understanding the full implications may require numerous harvests on 10- or 20-year cycles. For instance, the uneven-age management harvests in the CPL study were conducted for the seventh time in 2008, once in 1949 and once each decade thereafter, representing one of the longest-running examples of this type of uneven-age management in the eastern USA.

7.2.2 Treatments and Experimental Design

7.2.2.1 Demonstrations of CPLs

The CPL study was designed to demonstrate a range of residual stocking levels using different management intensities. Single-tree selection applying the balanced stand approach was used for uneven-age management. Residual stand goals were defined by three parameters: residual basal area (RBA), the largest tree to retain after each harvest in terms of diameter at breast height (dbh), and the ratio of trees in successively smaller size classes (*Q*), sometimes referred to as the BDq method of single-tree selection. The *Q* value results in a negative exponential size-class distribution (Fig. 7.2). Some forest scientists believed this type of stand structure to approximate the conditions that would develop naturally in older forests (Meyer 1952). Two levels of the BDq method were applied in the CPL study and both had a desired *Q* of 1.3 and a maximum dbh of 81 cm. The maximum dbh was deemed appropriate for the excellent growing conditions found at the site. In compartment 8D, the residual stand structure goals included both pole-size (minimum dbh of 18.0 cm) and sawlog-size (minimum dbh of 28 cm) trees and the targeted RBA was 20 m^2/ha. In subcompartment 8C, the residual stand structure goals included only sawlog-size trees, and the RBA for trees of that size and larger was 16 m^2/ha (Lamson and Smith 1991).

Both areas were first harvested after the 1948 growing season. Consistent with a 10-year cutting cycle, six additional harvests in each area have occurred, with the most recent in the fall of 2008. The diameter-limit harvest in the CPL study (8B) removed all trees larger than 39–cm dbh on a 20-year cutting cycle. After the first harvest in 1948, there have been three additional cutting cycles; the last harvest was in 2008. The commercial clearcut in the study (8A) removed all merchantable stems greater than 18.0 cm dbh in 1948 with no cull tree removal or additional silvicultural treatments to improve the next stand. This was not a true silvicultural clearcut but an exploitive type of harvest believed to be the "prevalent liquidation method of cutting" in 1948 (Weitzman 1949, p. 8). A second-rotation commercial clearcut is scheduled for 2018. A fifth area (8E) with similar site characteristics and disturbance history prior to the onset of experimental manipulations was also included as an unmanaged reference stand.

When the CPL study began, all areas were predominantly even-aged stands about 40 years in age with a few scattered older trees of poor form. All subcompartments were only 2 ha in size for demonstration purposes, and today the area remains easily accessible along a well-maintained and signed trail. Because of its easy accessibility, it is used for many guided tours to discuss the long-term implications of various types of forest management practices. Although demonstration was the primary purpose of the CPL study and therefore was not replicated for scientific testing, the treatments are similar to the LAMP study, which is replicated.

7.2.2.2 Studies in Large Area Comparison of Forest Management Practices

The LAMP study expanded the CPL concept to operationally sized units and featured three different site classes. The Fernow contains three broad site classes referred to as excellent, good, and fair and are estimated by northern red oak height growth. Excellent, good, and fair site classes relate to site index (SI) midpoints of 80, 70, and 60, respectively. SI has been used traditionally in terms of timber management to estimate potential wood volume growth and integrates several ecological factors such as soil type, aspect, landscape position, and precipitation, all of which are functionally related to the growth potential. SI also is a useful predictor of species associations and some ecological functions. Understanding how different sites shape the response to a silvicultural treatment such as single-tree selection greatly expands the geographic inferences that researchers can make from the results. An important benefit of the Fernow is that a range of sites exist and can be studied on a relatively small spatial scale (e.g., hectares $\times 10^3$); then research results can be extrapolated to a relatively large spatial scale (e.g., hectares $\times 10^7$).

Specific treatments in the LAMP study are uneven-age management, patch cutting in 0.16-ha openings, and a 43-cm diameter-limit cut. Unmanaged reference areas for each site class were also included and some treatments were modified for different site classes (Table 7.1). For example, larger trees were part of the residual stand

Table 7.1 Silvicultural treatments and compartments used for the Large Area Comparison of Forest Management Practices study initiated in 1950 on the Fernow Experimental Forest

Single-tree selection					
SI[a]	Cutting cycle (years)	RBA[b] ($m^2\ ha^{-1}$, $ft^2\ ac^{-1}$)	LDT[c] (cm, in.)	Q[d]	Compartment[e]
80	10	15 (65)	81 (32)	1.3	WS5A, 20A
70	10	12 (50)	66 (26)	1.3	7C, 16B
60	15	8 (35)	51 (20)	1.3	WS5B, 19B
Diameter-limit					
SI	Cutting cycle (years)	Harvest dbh[f] (cm, in.)			Compartment
80	15	43 (17)			WS2A, 9B
70	15	43 (17)			27A, 9A
60	20	43 (17)			WS2B, 20C
Patch cutting					
SI	Cutting cycle (years)	Rotation age			Compartment
80	10	65			18A, 17A
70	10	75			30, 18B
60	15	85			17C, 18C
Unmanaged					
SI					Compartment
80					WS4A
70					WS4B
60					WS4C

[a] Northern red oak site index, which is a measure of site quality (80 = excellent, 70 = good, and 60 = fair)
[b] Desired residual basal area of trees with dbh ≥ 28 cm (11 in.)
[c] Largest diameter-class tree to retain in the residual stand structure
[d] One measure of residual (postharvest) stand structure (see Fig. 7.2)
[e] See Fig. 7.1 for locations of compartments on the Fernow Experimental Forest
[f] Trees with dbh of 43 cm (17 in) or greater are harvested at each cutting cycle

goals on the more productive sites. The interested reader can find much more detailed information about this study in Schuler (2004). The patch cutting treatment in the LAMP study provides an opportunity to study stand dynamics in openings that are smaller than conventional clearcuts but large enough to establish groups of trees of the same age. In theory, patch cutting results in an uneven-aged stand structure made up of small even-aged patches. The LAMP diameter-limit harvest is not considered a silvicultural treatment, in part because there are no residual stand objectives. A simple diameter-limit harvest is considered an exploitive harvest, but it is one of the most common forms of timber harvesting in the central Appalachians (Fajvan et al. 1998) because it provides revenue with few internalized costs to the landowner.

7.2.2.3 FMDL Studies

The FMDL concept was conceived as a potential replacement for diameter-limit cutting in order to maintain quality and productivity in the residual stand, still provide an acceptable rate of return, and entail less complexity than other more conventional approaches to uneven-age management. George R. Trimble Jr., a Fernow scientist and project leader from 1950 to 1954 and 1957 to 1973, developed the procedure because he believed that good forest stewardship was achieved through sound ecological and economic principles, but too much complexity would deter acceptance and use. Trimble wrote that the predominantly second-growth forests created by the large-scale exploitive harvesting in the late 1800s and early 1900s created conditions where the traditional concepts of uneven-age management were difficult to apply (Trimble et al. 1974). The approach he developed estimates individual tree financial maturity and outlines when each tree should be harvested based on financial objectives and the growth potential of the site. Unlike diameter-limit cutting, FMDL directs the user to select residual stocking levels by simple guidelines referred to as rates of return. The Fernow FMDL study used three rate-of-return treatments (3, 4, and 6 %) and each treatment was replicated in two compartments (Schuler and McGill 2007). Similar to more conventional approaches to uneven-age management, the first priority is removing all trees of poor quality and low vigor (Trimble et al. 1974). But unlike true single-tree selection, the marking procedures are much easier to use in the field once some guidelines have been selected. Balancing growth with removal is a fundamental principle of all uneven-age silviculture and an equally important component of the FMDL system.

7.3 Results and Discussion

7.3.1 Species Composition and Diversity

A common theme among all three studies has been the general decline of oaks and all other shade-intolerant species, including the commercially important black cherry (*Prunus serotina*), coupled with an increase in the abundance of shade-tolerant species, especially sugar and red maple. The proportion of sugar maple has risen from about 15 % in 1950 to observed levels that exceed 50 % recently in the overstory on many excellent growing sites (Schuler and Gillespie 2000). Current understory dominance of sugar maple is even greater, suggesting that the trend of increasing dominance by this shade-tolerant species will continue. Trimble (1965) predicted that cove hardwood stands in the central Appalachians that were subjected to some type of partial harvesting regime (e.g., single-tree selection or diameter-limit harvesting) would eventually be dominated by sugar maple.

The observed levels of sugar maple dominance today are nonetheless unprecedented. Early in the last century, Brooks (1911) estimated that sugar maple accounted for about 10 % of the composition of the remaining old-growth hardwood forests in the vicinity of the Fernow. Looking back even further, researchers have studied pollen deposits that suggest sugar maple was not the most abundant species in the region at any time since the end of the Wisconsin glaciation about 17,000 years ago (Larabee 1986). Furthermore, no evidence suggests that current trends will abate or that species composition will shift back to the more diverse mixtures of the nineteenth and twentieth centuries (Schuler and Gillespie 2000). Loss of certain species means reduced food for wildlife and less resilience in the face of known and unknown perturbations yet to occur such as climate change, invasive plant species, and new insect pests. The reduction in diversity, clearly captured on the Fernow, is widespread throughout the central and eastern hardwood regions and has been referred to as the "mesophication" of the hardwood forest types in the eastern USA (Nowacki and Abrams 2008). Although patch cutting in openings about 0.16 ha in size has sustained some shade-intolerant species, none of the treatments has avoided the significant decline in oak abundance (Schuler 2004). Maintaining the compositional diversity of Appalachian forests and forest types is a high priority for the Monongahela National Forest (USDA Forest Service 2006) and other land management agencies in the eastern USA (Nowacki et al. 2009).

In the 1960s, as Trimble (1965) and researchers at the Vinton Furnace Experimental Forest in Ohio reported their findings regarding how only a few species were thriving following uneven-age management, USDA Forest Service scientists were advising National Forest managers to turn to even-age management, often in the form of clearcutting, to regenerate shade-intolerant species (Roach and Gingrich 1968). To achieve desired harvest levels and stay within budget for new road construction, clearcutting grew in size from tens to hundreds of hectares and sometimes were located in close proximity to each other over a period of years (Cravens 1975). Public opposition and controversy regarding how timber should be harvested from public land soon followed. When citizens objected to clearcutting, Forest Service managers cited research in West Virginia and Ohio (Trimble 1965; Roach and Gingrich 1968) to explain why they needed to move away from partial cutting or uneven-age management (H. Clay Smith, personal communication, 2009). But fear of a return to the vast exploitive harvesting that had ended just a half century earlier ultimately led to significant social conflict about whether clearcutting should be allowed. Finally, a legal decision about clearcutting (*West Virginia Division of the Izaak Walton League of America, Inc. v. Butz* 1973), sometimes referred to as the "Monongahela Decision," led to a temporary ban on all clearcutting in some eastern National Forests (Haines 1976) and ultimately to the passage of important federal legislation affecting the management of all National Forests (i.e., National Forest Management Act of 1976; Haines 1976).

As these historical events unfolded in the 1960s and 1970s, researchers continued to look for silvicultural options that would meet management objectives and be socially acceptable. The uneven-age management research on the Fernow continued to be evaluated as part of the research portfolio of alternative silvicultural options. Clay Smith, Fernow Research Forester and Project Leader from 1962 to 1967 and 1973 to 1994, stated that "the demonstration value of the uneven-age management studies during the clearcutting controversy was critical; everyone wanted to see examples of both even-age and uneven-age management first-hand and learn the pros and cons of each" (H. Clay Smith, personal communication, 2009). Legislators, members of the USDA Forest Service leadership team, and the general public took advantage of the Fernow's convenient location, approximately half a day's drive from Washington, DC, to see how these two contrasting practices looked on the ground (H. Clay Smith, personal communication, 2009). This period of controversy reinforced the need to have examples of a range of silvicultural practices that are easily accessible to the public, policy makers, and executive branch officials. Interest in seeing the treatments in person continues to this day and has become a major part of the technology transfer effort at the Fernow.

The interaction among scientists, managers, policy makers, and the public also produced a new silvicultural technique, sometimes referred to as "two-age" management, which addressed several of the issues. The first installations of two-age management were on the Fernow and other locations on the Monongahela National Forest. For a more detailed account of how this innovative technique emerged from the controversy surrounding the Monongahela Decision, see Miller (this volume). Knowledge and insight gained from this work are now based on more than 25 years of research and experience (Thomas-Van Gundy and Schuler 2008). Although no single system will ever satisfy every forest regeneration need, the collaboration among scientists and managers that developed two-age management, with input from concerned citizens, is a model of how future forest management issues can be addressed in a timely and effective manner.

As the long-term silvicultural experiments have continued on the Fernow and elsewhere, scientists have gained more insight into the effects of uneven-age management. In the Fernow studies, which included a range of site classes, sugar maple dominated the regeneration on the better sites and red maple dominated it on the poorer sites, especially in conjunction with any type of partial harvesting treatment. In general, of the 32 species identified in the overstory from 1951 to 2001, only American beech (*Fagus grandifolia*) and black birch (*Betula lenta*) increased in importance, apart from the maples already noted. All other species declined or remained minor components of the stand. Compartments managed with single-tree selection declined the most with respect to diversity and the decline was most pronounced on the better-quality sites (Schuler 2004). Fortunately for forest landowners interested in sustaining a periodic income, the commercial value of sugar maple is relatively high compared to that of other species. The commercial value of American beech, another shade-tolerant species that often increases following repeated partial harvests, is much less, however.

Responsible forest management embraces the concept of species diversity as a hedge against future changes in species' relative values and species- or genera-specific pathogens. For example, chestnut blight fungus, accidentally introduced into North America in the early twentieth century, effectively eliminated American chestnut (*Castanea dentata*) from eastern forests and urban settings in just a few decades (Anagnostakis 1987). Today in the eastern USA, up to ten nonnative insects or diseases threaten the forests of the eastern USA (Orwig 2002) and forest management strategies play an important role in minimizing their impacts (Waring and O'Hara 2005). Avoiding monocultures or forest stands that are dominated by one species reduces the risk of catastrophic mortality. Moreover, when management practices also reduce diversity, current forests are less reflective of historic (Schuler and Gillespie 2000) and prehistoric (Delcourt and Delcourt 1987) conditions and are less able to provide a full suite of forest products, wildlife needs, and ecological services.

The extent to which uneven-aged management (or no management) has contributed to the decline of many tree species suggests that the conditions created by single-tree canopy openings do not reflect conditions that permitted many species to persist in the past. Recent work suggests that oaks and other species had multiple canopy accession pathways before the twentieth century, including both large and small canopy openings (Rentch et al. 2003). It is therefore likely that the decline of oaks and sympatric species, which is associated with partial harvesting and uneven-age management, results from multiple factors. In the central Appalachians and elsewhere, increased deer abundance, loss of fire as a periodic understory disturbance, and changes in understory composition related to invasive species (both native and exotic) contribute to oak decline (Abrams 1992). In 1973, Fernow scientist George Trimble wrote that "deer browsing on the Fernow or in most of West Virginia is not a serious deterrent to obtaining satisfactory oak reproduction" and estimated the deer herd at six deer per square kilometer (Trimble 1973). But today, deer populations have increased dramatically and can be a limiting factor to obtaining adequate forest regeneration, regardless of the type of forest management used (Horsley et al. 2003). Foresters have used deer exclusion fencing, prescribed burning, and herbicides to overcome a variety of limitations to achieving adequate regeneration, but generally these techniques were associated with even-age management in the last century (Brose et al. 2008). The utility of these and other forest management practices in conjunction with uneven-age management has not yet been fully considered. New studies are underway at the Fernow to test how prescribed fire and deer influence regeneration following partial harvesting.

It should further be noted that uneven-age management is not always based on harvesting single trees and making small gaps in the forest overstory. Much larger gaps of one to several hectares could be included in one type of uneven-age management known as group selection. Group selection has been evaluated on the Fernow, and the LAMP study does include harvesting in 0.16-ha patches. In some cases, these patch openings have been satisfactory for regeneration of shade-intolerant species, but the oaks and hickories are not usually successful in such openings (Miller and Schuler 1995).

One of the unexpected benefits of uneven-age management and other long-term partial harvesting practices on the Fernow has been the apparent creation of a suitable habitat for the federally endangered running buffalo clover (*Trifolium stoloniferum*). Running buffalo clover prefers sunlight from small canopy gaps and canopy densities associated with various forms of partial harvesting (Madarish and Schuler 2002). This clover was once thought to be close to extinction and was listed as federally endangered in 1987. In 1993, it was discovered on the Fernow Experimental Forest, where it is now recognized as one of the largest occurrences of running buffalo clover known to exist. Nearly all of the running buffalo clover on the Fernow occurs in locations used for uneven-age management research and demonstration. Research continues to better understand why the conditions created by uneven-age management are so conducive to running buffalo clover persistence and how to fully recover this species (Burkhart 2010). It has also been shown that where running buffalo clover thrives, there is a much more diverse herbaceous community

(Burkhart 2010). Thus, while woody species diversity is declining in conjunction with uneven-age management, there appears to be a guild of herbaceous species that benefit from the repeated moderate level of disturbance associated with this type of harvesting and management.

7.3.2 Productivity

Surprisingly, unlike the loss of woody species diversity following decades of uneven-age management on the Fernow, productivity has met or exceeded levels expected for managed stands in all three studies and the importance of the effect of stocking on productivity has been demonstrated. After a half century of research in the LAMP study, growth in cubic wood volume as measured by mean periodic annual increment (PAI) ranged from 4.0 to 4.6 m^3/ha/year for all managed stands, but averaged just 2.5 m^3/ha/year for the unmanaged reference areas (Schuler et al. 2006). The documented growth rates illustrate that when managed properly, forest stands such as these are commercially important and are capable of growing high-quality wood products for a sustained period of time, as well as providing important ecological services.

Fernow scientist Trimble (1965) predicted declines in productivity as shade-tolerant species increased, but the effect of the documented changes in species composition appears to be less important than that of residual stocking. For example, despite increased maple dominance, productivity actually increased in some instances. Mean PAI for the diameter-limit-treated areas (SI = 70 and 80 combined) in the LAMP study increased from 4.3 to 4.8 m^3/ha/year from the first to last cutting cycles despite the loss of most shade-intolerant species. With respect to compartments managed with single-tree selection, declining trends in productivity are suggested graphically, but not statistically (Fig. 7.3; Schuler et al. 2006). Aside from environmental factors associated with site conditions, stocking is the most important factor associated with productivity. Uneven-age management conducted properly strives to maintain stocking at levels that will allow forest growth to remain vigorous for long periods of time.

The general relationship between growth and stocking is robust and an inherent part of many forest management guidelines for both commodity and non-commodity resources. In general, productivity is optimized at a stocking level that fully occupies the growth potential of a site and then declines as increased crowding reduces growth efficiency. This is the case as an even-aged stand develops through time and is clearly illustrated by the commercial clearcut and the unmanaged reference treatment areas in the CPL study (Fig. 7.4). In other words, growth continues, but the rate of growth declines as the stand gets more crowded. In contrast, with uneven-age management, residual stocking control is an inherent part of the process. By maintaining stocking in a more optimal range, productivity can theoretically be maintained at higher levels, such as the case with the single-tree selection and diameter-limit treatment areas in the CPL study (Fig. 7.4).

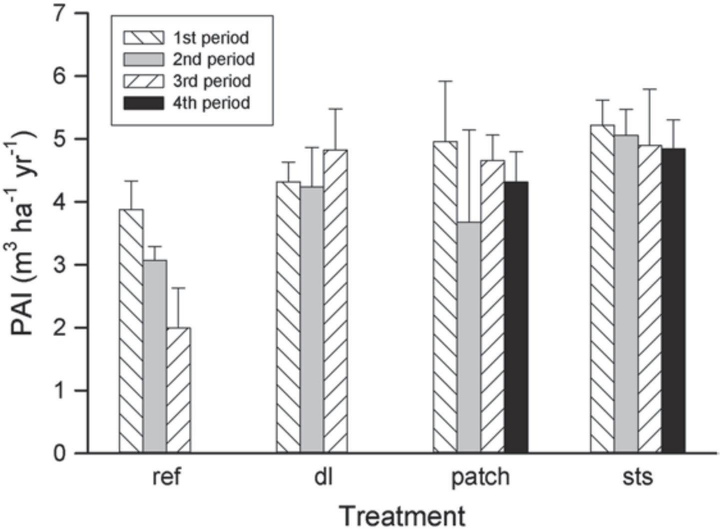
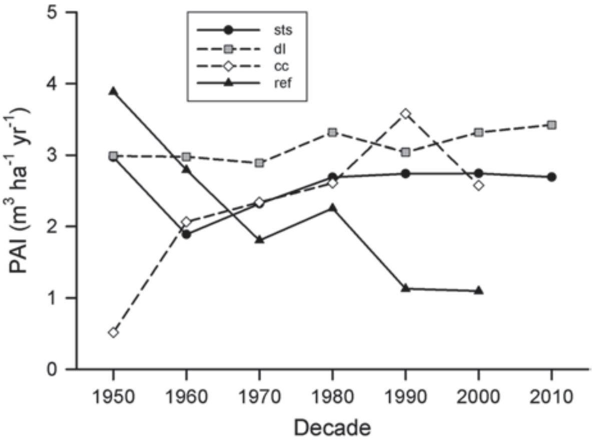


Fig. 7.3 Mean cubic volume net periodic annual increment (PAI) of merchantable trees (dbh ≥ 12.7 cm, 5.0 in.; vertical lines = 1 standard error) by measurement cycle and treatment category for good and excellent sites in the LAMP study (*ref* unmanaged reference compartments; *sts* single-tree selection; *dl* diameter-limit; and *patch* patch cutting)

Fig. 7.4 Cubic volume net periodic annual increment (PAI) of merchantable saw-log-size trees (dbh ≥ 27.9 cm, 11.0 in.) by measurement cycle and treatment in the CPL study (*ref* unmanaged reference compartment; *sts* single-tree selection (8C only); *cc* commercial clearcut; and *dl* diameter-limit. Note that cubic volumes here were converted directly from board feet, thus providing a conservative estimate of productivity



In the FMDL study, one of the opportunities was to evaluate the three rate-of-return levels to better understand their effects on the stocking and productivity relationship. After four periodic harvests, real distinctions in productivity have emerged, especially between the 3 and 6 % rate-of-return treatments. The 6 %

treatment yielded more than 29 m^3/ha/decade of cubic wood volume[1] in the second and third harvests, and more than 23 m^3/ha in the last decade (Schuler and McGill 2007). In contrast, the 3 % treatment is averaging a little more than 17 m^3/ha/decade and declined below that level in the last harvesting cycle. The 6 % treatment had the lowest RBA among treatment and time period interactions and was even below the recommended residual basal range of 13 m^2/ha (Trimble et al. 1974).

Some unexpectedly high growth rates associated with low RBAs were also documented in the CPL study. The diameter-limit treatment in this study resulted in a mean postharvest basal area after four cutting cycles of about 9 m^2/ha (dbh $\geq$ 12.7 cm). Yet the PAI resulted in the highest level of sustained productivity among all of the treatments (Fig. 7.4) and was well above the expected growth rate.

The unexpected level of productivity associated with low levels of residual stocking in all three long-term studies suggests our understanding of the stocking and productivity relationship is incomplete in the central Appalachians. Now that the carbon sequestered in forests is recognized as an important contributor to the global terrestrial carbon sink, it is more important to fully understand how growth rates are influenced by silvicultural prescriptions and management choices. Recent work on the Fernow using long-term measurements of water, carbon, and nitrogen in four different watersheds with different harvest histories has shown that forests managed with single-tree selection or diameter-limit harvesting stored about 37 % more carbon than did forests that were not harvested during the past half century (Davis et al. 2009). These findings are consistent with the higher growth rates documented in all three long-term studies on the Fernow where some form of partial cutting or uneven-age management has been employed. These findings have potentially important implications for managing greenhouse gases in the twenty-first century. The long-term measurements and forestry manipulations on the Fernow allow scientists to ask questions never anticipated 50 years ago, such as calibrating models of ecosystem productivity and understanding the state of carbon in forests managed using different scenarios. The partial cutting approaches on the Fernow may enhance the utility of forests as carbon sinks—at least for now. Understanding how forests and species respond to predicted changes in climate (Iverson and Prasad 1998) will be vitally important in the twenty-first century, and knowing how forests functioned prior to that period will be the benchmark for comparison.

7.3.3 Economic Considerations

Diameter-limit harvesting is by far the most common type of harvesting in eastern hardwoods (Fajvan et al. 1998). However, the repeated removal of commercial products with no investment in residual stand quality will lower residual stand values. Without regeneration of a commercial tree species, the residual for-

[1] Here, volume estimates were based on board feet which incorporate a loss in total volume due to sawing requirements. Cubic volume estimates are direct English to metric conversions (Miyata et al. 1981) without building the loss back into the estimate.

est stand may eventually have little to no commercial value. After six decades, the CPL study provides an excellent case study to examine this subject. Net present value (NPV) for each payment for each treatment was calculated using an internal rate of return (IRR) of 4% and a market rate of return (MRR) equal to the mean inflation rate for the period of interest plus the IRR. Residual stand values in 2008 also were calculated based on local 2008 timber sale bid rates for each species.

As expected, after six decades and four harvests, the diameter-limit residual stand value was the least among all of the treatments, but its NPV based on the MRR of all past timber-based revenues was the greatest (Table 7.2). The residual stand value of the unharvested stand (8E) was about US$ 19,760/ha and greater than any of the harvesting treatments, but its present value including the value of past payments was the lowest. All forms of management that included some form of harvesting resulted in a present value that was about three to five times greater than that of the unharvested stand. Accordingly, it is easy to understand why private forest landowners have been motivated to manage their forestland for periodic revenue. It appears that substantial revenue can be sustained about once per decade on managed land on excellent growing sites. Most recently, payments declined (Table 7.2), but this decline was due to a decrease in timber values caused by a historic downturn in the economy and not due to a decrease in wood quantity or quality.

It is also noteworthy that the residual stand values in 2008 for the single-tree selection compartments (8C and 8D) were about US$ 9,880/ha, or about half of the value of the unharvested compartment (8E), even though there had been at least seven previous harvests in these two compartments. Maximizing NPV is only one aspect to consider when managing forests and the value of past payments has little to no relevance to future revenue potential. Few forests are managed to optimize NPV, but our calculations and recorded payments illustrate the allure of partial cutting, especially diameter-limit cutting. Modifying partial harvests so that they can produce periodic income and maintain diversity and structural goals remains an important aspect of modern forest management research. Any management that favors the preponderance of one species over a diverse mixture of species provides less insurance against changes in consumer preferences, which could influence relative species values in the future. Moreover, some climate change scenarios predict sugar maple will become less suited to the region as temperatures warm (Iverson and Prasad 1998), so avoiding sugar maple dominance seems wise under those scenarios. However, when a desirable tolerant species can be regenerated at each periodic harvest, uneven-age management can be a realistic management alternative that can provide an acceptable rate of return (Miller 1993), while providing the benefits of continuous forest cover (Fig. 7.5).

7.4 Summary

Interest in uneven-age management on the Fernow Experimental Forest was in part a reaction to the forest exploitation era that occurred in the central Appalachian Mountains from about 1880 to 1920. After World War II, a more sustain-

Table 7.2 Fernow Experimental Forest Cutting Practice Level harvest payments and present values as of 2008 (USD ha^{-1}) using a risk-free rate of return (4 %) and a market rate of return adjusted for inflation in the USA

ID	Year	Payment	Present value (4 %)	Present value[a] (market rate)
8A	1949	694	7,022	57,077
	Residual timber in 2008		*14,600*	*14,600*
	Total		21,622	71,677
8B	1949	506	5,113	41,568
	1968	1,623	7,795	45,841
	1988	2,729	5,977	10,678
	2008	6,375	*6,373*	*6,375*
	Total payments		25,258	104,462
	Residual timber in 2008		*4,453*	*4,453*
	Total		29,711	108,915
8C	1949	321	3,243	26,370
	1958	128	914	6,375
	1968	277	1,334	7,842
	1978	889	2,885	9,537
	1988	946	2,075	3,705
	1998	4,881	7,225	9,248
	2008	2,505	*2,505*	*2,505*
	Total payments		20,181	65,582
	Residual timber in 2008		*9,166*	*9,166*
	Total		29,347	74,748
8D	1949	282	2,858	23,233
	1958	121	852	5,945
	1963	59	351	2,275
	1968	193	924	5,429
	1978	1,633	5,293	17,505
	1988	1,919	4,206	7,511
	1998	4,723	6,993	8,949
	2008	2,354	*2,354*	*2,354*
	Subtotal		23,831	73,201
	Residual timber in 2008		*9,934*	*9,934*
	Total		33,765	83,134
8E	2008		19,775	19,775

Compartment 8A was commercially clearcut in 1949; 8B was harvested using a diameter-limit (39.4 cm dbh) with a 20-year cutting cycle; 8C (includes trees 27.9 cm dbh and larger) and 8D (includes trees 12.7 cm dbh and larger) were harvested using single-tree selection once per decade; and 8E serves as an uncut reference stand of similar disturbance history prior to 1949

[a] Present values using market rates were computed using periodic rates of inflation. Annual inflation rates in the USA from 1949 through 2007 ranged from −0.95 to 13.58 % and averaged 4.41 %

able type of forest management was desired and interest in uneven-age management grew as a result. The Fernow became one of several Forest Service Experimental Forests in the eastern USA where this interest led to the establishment of long-term studies to better understand the consequences of a wide range of silvicultural options.

Fig. 7.5 A 60-year photo series from the CPL study (compartment 8C, camera point 4) managed with single-tree selection from 1948 to the present using 10-year cutting cycles. The sequence of images illustrates the decay of large coarse woody debris, the removal of trees through harvesting, and the growth of residual trees. Note the arrow pointing to the same tree in each image (a through d, 1948, 1958, 1979, 2008, respectively)

After more than a half century of uneven-age management research, much has been learned. The results illustrate that the mixed-mesophytic forest type, with its shade-tolerant commercial species, is capable of maintaining acceptable levels of productivity and stem quality, although concomitant reductions in woody species diversity are a byproduct and a serious management concern. Uneven-age management is shaping species composition in a way that seems to accelerate ongoing successional trends, and these trends may be unprecedented and counterproductive to some long-term management objectives. We have also demonstrated that simple diameter-limit harvesting may seem more profitable, at least for a few decades, but leaves the forest with less potential for future revenue. In so doing, however, we have also learned that lower levels of residual stocking, associated with more exploitive types of periodic partial harvesting, are not necessarily counterproductive to optimizing growth and carbon sequestration. Further research is needed to better understand the relationships among stocking, growth, and species recruitment, especially in the face of predicted climate change scenarios. Along with other Forest Service research units, we have learned that the original value-laden treatment names (e.g., excellent, good, fair, or poor cutting practice) associated with some early uneven-age management research were based on faulty assumptions, illustrating the need to test commonly held theories in forest stand dynamics. Both even-age and uneven-age management techniques can be used appropriately, depending on the circumstances, but the ecological amplitude of individual species must be recognized. For example, when individual tree canopy gaps constitute the largest planned opening in a forest, such as with single-tree selection, it is unreasonable to expect shade-intolerant species to be sustained.

Uneven-age management research is a long-term endeavor because the forest is changed gradually through time, at each harvest, and by unplanned perturbations. Determinations of sustainability are related to the simultaneous processes of growth, harvest and death, and regeneration, as well as social acceptance and economic viability. When the early researchers Sydney Weitzman and George Trimble Jr. planned the uneven-age management research on the Fernow, the objectives clearly involved the sustained yield of commercial forest products. They could not foresee the many changes ahead, such as the clearcutting controversy that came to a head in the 1970s; new federal laws pertaining to the protection of rare species, environmental assessments, and public involvement in the forest planning process; radically increased deer abundance affecting forest regeneration; exotic pests and invasive species displacing native ones; and the emerging issues of climate change and the related role of forests as carbon sinks or sources. Testing, developing, and refining uneven-age, even-age, two-age, and new forest management techniques remain a critical need and a vital part of the long-term mission of the Fernow Experimental Forest. Yet opportunities for exploring unanticipated issues will continue to be an important dimension of the research at the Fernow. Lindenmayer et al. (2010) refer to the discovery of unanticipated findings as "ecological surprises" and assert that such discoveries are more likely detected as part of long-term research because time is a major driver of change. In the absence of long-term forest research, it is difficult to identify changes in populations, ecosystems, or ecological processes because the reference conditions or processes are not well documented. We will continue to identify new forest research objectives as the world changes and new issues emerge. It is a virtual certainty, however, that healthy and productive forests will remain an essential societal objective and be part of a sustainable twenty-first century for everyone.

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