Chapter 13

Silviculture for Eastern Old Growth in the Context of Global Change

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When management for old-growth characteristics in eastern forests first began to be discussed in the late twentieth century, there was skepticism from some quarters as to whether it was a desirable or even a feasible idea. Old growth will recover on its own. Why not just let nature take its course? There were also those who saw little value in managing for old-growth features, perceiving this as a threat to more traditional management objectives (Puettmann et al. 2015). Since that time, concepts of managing for stand structural complexity, in ways that encourage some characteristics of old-growth forests, have caught on in a variety of contexts (Bauhus et al. 2009; Puettmann et al. 2009). In many ways this shift mirrors how the profession has grown to embrace multifunctional forestry broadly defined (Gustafsson et al. 2012). Old-growth silviculture increasingly has a place within this framework, filling the niche of enhancing the representation of late successional forests on landscapes where they are now vastly underrepresented relative to their abundance on landscapes prior to Euro-American settlement (Lorimer and White 2003; Rhemtulla et al. 2007). The working hypothesis is that this type of management will contribute to sustainable forest practices focused on providing a broad array of ecosystem goods and services, including those associated with late successional systems. And in recent decades there has been increasing interest in old-growth restoration more narrowly and management for older forest characteristics in working forests generally, both in terms of experimental research (e.g., Keeton 2006; Gronewold et al. 2010; Forrester et al. 2013; Palik et al. 2014) and practical applications (Hagenbuch et al. 2013; Fassnacht et al. 2015).

Interest in structure-based silviculture has evolved from studies demonstrating the ecological significance of specific structural elements associated with late successional and old-growth forests (e.g., Tyrell and Crow 1994; McGee et al. 1999; Ziegler 2000; Després et al. 2014). Availability of these structures can be highly limited in forests managed under conventional even- and uneven-aged systems (Hale et al. 1999; McGee et al. 1999; Angers et al. 2005). But a central question remains: Is it better to let old growth recover passively or could silvicultural methods be used to restore or increase the representation of old-growth characteristics in secondary forests? Certainly it has become clear that humans have often negatively impacted forests, even in remote locations, in ways that nature cannot readily rehabilitate. Moreover, old distinctions between active forest management and natural-areas management have become blurred in recent decades. No longer are these distinctions viewed as a strict dichotomy (Keeton 2007). Agencies such as the National Park Service and organizations like The Nature Conservancy now routinely conduct prescribed burning, cut or thin undesirable trees, reestablish native species, and apply herbicides to control invasive plants (Schwartz et al. 2016). In the Anthropocene, the idea of just letting nature take its course no longer seems to be an adequate strategy if the goal is to maintain biologically diverse and healthy ecosystems that function in a similar way to forests in the past millennium. Especially in the eastern United States, where most forests even in reserves have been cutover one to several times, and the existing forest is increasingly subject to a blitzkrieg of novel stressors—invasive species, exotic earthworms, and airborne pollutants—passive management could result in depauperate ecosystems under chronic stress. Yet, it is clear that these novel stressors will make restoring, or even just maintaining, old-growth structural features technically challenging.

One reason for considering active management in eastern North American forests is an issue of time delay. Even if passive management could restore healthy old-growth forests, the process in the existing second growth would often involve a delay of another 60 to 150 years. Old growth is currently so rare that treatments in younger forests to accelerate old-growth structural features—large trees, canopy gaps, multilayered vegetation, standing snags, and fallen logs—have demonstrated ecological benefits (e.g., Bauhus et al. 2009; Dove and Keeton 2015). These benefits range from the late successional habitat values provided by such structures, to ecosystem service benefits like enhanced carbon and riparian functionality. The biodiversity argument is nuanced and focused on correcting the forest age class imbalances that are the legacy of the region's land-use history. In the Pacific Northwest, for example, over a thousand species were deemed strongly associated with late successional ecosystems (FEMAT 1993). But here in the East, the biodiversity value rests primarily on habitat quality and availability for species using late successional/old-growth habitats (figure 13-1; chapter 11). In our region only rarely does the biodiversity depend strictly upon old-growth habitats, although there are notable exceptions like some calicioid lichens and fungi (Selva 2003; chapter 11). But populations of often underrepresented late successional species would benefit from having more old-growth structures available in reserves, and more importantly, if these structures were better incorporated into managed landscapes comprising the majority of eastern forests.

We stress that management for late successional biodiversity is by no means mutually exclusive of early successional habitat management advocated for species such as disturbance-dependent birds (see, for example, Hunter et al. 2001). Early and late successional habitats share high biodiversity value (figure 13-1). The question is how best to optimize the mix of all habitat types at landscape scales. In other words, forest managers can provide both early and late seral habitats with careful planning and forest harvest scheduling. However, it will be important to consider the long-term implications for forest age class distributions of increased emphasis on early successional management. This is needed to avoid the unintended consequence of a landscape shifted over time by techniques like patch cutting into the stem-exclusion stage of development, which most often has the lowest biological diversity of any structural condition (figure 13-1).

In some ways, ecosystem service benefits are the most compelling reason to incorporate old-growth siviculture into holistic management. Often, forest managers and landowners in the eastern United States—spanning a huge range of ownership systems, parcel sizes, and degrees of timber emphasis—are most interested in sustainable forest management integrating multiple cobenefits. Chief among the ecosystem service values cited as an outcome of old-growth silviculture is climate change mitigation through enhanced carbon storage. Sequestered carbon in the form of biomass stored above- and belowground is many times higher in landscapes with abundant old-growth forests as compared to most managed landscapes (Rhemtulla et al. 2009; Keeton et al. 2011; McGarvey et al. 2015). Consequently, the types of high biomass structural conditions targeted by old-growth silviculture are precisely what are incentivized by rapidly developing compliance and voluntary carbon markets (Kerchner et al. 2015). It is no surprise, therefore, that old-growth silviculture often makes use of similar techniques (e.g., high degree of retention, extended rotations, enhancement of large tree and dead wood components) as those recommended for carbon forestry (Nunery and Keeton 2010; see chapter 14). Similarly, there is growing interest in the high

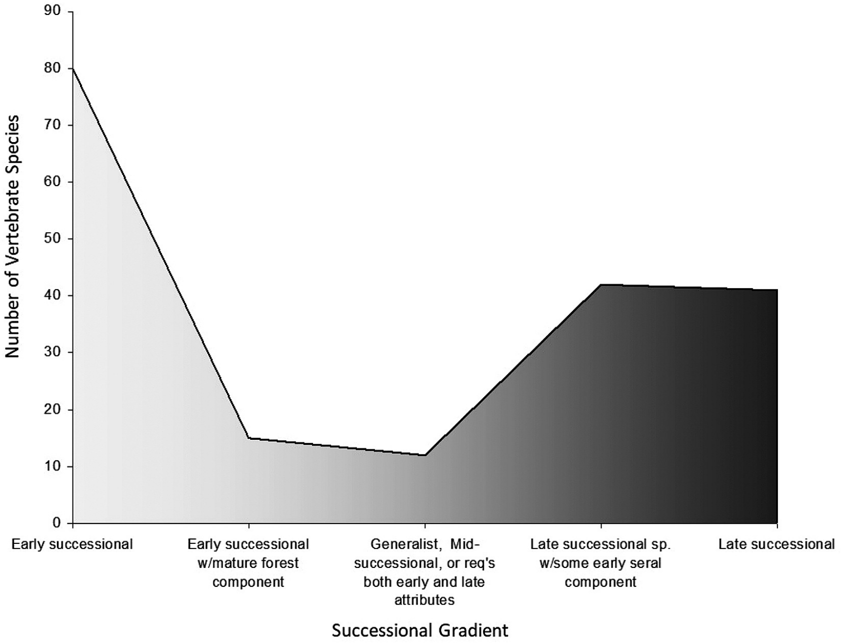

FIGURE 13-1. Number of vertebrate species in northern hardwood forests of New England, categorized by seral stage and habitat association. The data were extracted by K. Manaras-Smith, E. Travis, and W. S. Keeton (unpublished) from matrices published in DeGraaf and Yamasaki (2001). The categorizations are based on habitat preference and use scores developed by Manaras-Smith et al. from the various habitat uses, requirements, and associations presented in the matrices. When these scores where arrayed along a size class gradient (regenerating, pole-sized, sawtimber, large sawtimber, and uneven-aged), the use scores for large sawtimber and uneven-aged stands were more than twice that for regenerating and pole-sized stands; they were 70 percent greater for preference scores. However, when overlapping or multiple habitat uses (e.g., by the same species) were assessed, as displayed on the X axis in the figure above, the relationship took on a U-shaped form. This indicates the strong biodiversity value of both early and late successional habitats, as well as seral habitats with biological legacies and some attributes of both early and late successional forests.

degree of riparian functionality provided by structurally complex, late successional forests, particularly in terms of effects on stream habitats (Keeton et al. 2007; Warren et al. 2016) and flood resilience (Keeton et al. 2017).

At the same time, it should be recognized that old-growth management and retention of large legacy trees, while probably economically feasible, will likely reduce rates of stand production to some degree. This has already been reported in Douglas-fir forests of the Pacific Northwest (Zenner et al. 1998) and in southern Appalachian forests (Miller et al. 2006). In northern hardwoods, a simulation of 22 ecological forestry treatments with an individual-tree model suggested that reduced production could vary widely depending on the treatment. These ranged from a 9-percent decline with 7 reserve trees per hectare to a 55-percent decline with treatments retaining substantial coarse woody debris and a maximum residual DBH (diameter at breast height) target of 80 centimeters. Treatments designed to strike a balance between timber production and maintenance of old-growth stand structure involved losses of 27 to 30 percent compared to conventional single-tree selection (Hanson et al. 2012). In an experimental study in Vermont, a technique designed to accelerate the development of old-growth characteristics harvested only 60 percent of the merchantable volume produced by conventional selection harvests, but generated a moderate profit when market conditions, preharvest volumes, and trucking distances were favorable (Keeton and Troy 2006). With the advent of carbon markets providing financial incentives for forestry practices that maintain high stocking levels, we may see old-growth silviculture tapping into supplemental revenue streams in the future.

A major impediment to restoration of old-growth features—and one that has no easy solution in sight—is the recent cascade of novel and interacting environmental stressors, such as climate warming, exotic insects, diseases, earthworms, excessive deer densities, and invasive plants (see chapter 12). Insects, diseases, and drought often disproportionately affect large and old trees, hampering efforts to restore or maintain old-growth structure. The continued presence of old trees of susceptible species seems unlikely in the near future without some effective mechanism (e.g., biological control, backcrossing, genetic engineering—all contentious and fraught with challenges) to combat the attacking organisms. In addition to exotic pests and pathogens already well established in eastern North American forests, such as chestnut blight (*Cryphonectria parasitica*) and emerald ash borer *(Agrilus planipennis*), new ones, such as Asian long-horned beetle (*Anoplophora glabripennis*), mountain pine beetle (*Dendroctonus ponderosae),* and sudden oak death (*Phytophthora ramorum*), are on the horizon and may be capable of major devastation for multiple species. Given these potential realities, the principles of managing for old growth in this chapter should probably be regarded in the short term as interim guidelines for areas not yet heavily impacted by environmental stressors. Over the long-term, silviculture oriented toward old growth—like all forestry—will need to adapt to changing environmental conditions.

Lessons from Old Growth

Traditionally, old growth was treated as a predictable and stable end point of forest development (Odum 1969; Bormann & Likens 1979). But the contemporary view rejects the idea of a stable "climax" stage, recognizing instead the potential for continuous change (termed "nonequilibrium dynamics") as old, complex stands are acted upon and respond to a range of natural disturbance types and intensities that occur chronically, periodically, or episodically (Ziegler 2002 ; D'Amato and Orwig 2008). Work in recent decades has shown that forest structure and composition continue to fluctuate after old-growth age thresholds are crossed (Spies 1997). In Pacific Northwest forests, varying degrees of old growth have been described (Franklin et al. 2002). In eastern forests, continuous changes in forest elements, such as gap fraction, coarse woody debris volume, biomass, and relative species abundance, have been observed across chronosequences, on permanent plots, and projected in simulations (Tyrrell and Crow 1994; Woods 2000; Keeton et al. 2011). Developmental stages in the live-tree population can be detected from systematic changes in the diameter distribution of old-growth stands, which tend to develop from unimodal to bimodal (compound) to descending monotonic in the absence of moderate or heavy disturbance (Lorimer and Halpin 2014). In the Great Lakes region, which has some extensive and rather pristine landscapes of old growth, all these stages are evident on the landscape as a patchwork, with roughly equal proportions of old growth in the different stages (Heinselman 1973; Lorimer and Halpin 2014).

In late successional forests, however, these stages do not appear to develop along a simple circular pathway from a young, even-aged forest to uneven-aged old growth, reverting to a young forest again after a stand-replacing disturbance (as in Bormann and Likens 1979). Rather, the pathways resemble a complex web, with stands moving backwards and forwards in erratic and unpredictable fashion among various stages in response to repeated mild and moderate disturbances (Hanson and Lorimer 2007; Halpin and Lorimer 2016; Meigs and Keeton 2018). Complicating things further are the effects of land-use history (e.g., wood harvesting, pests, pathogens, etc.) on long-term trajectories for forest development, resulting in a structure and composition that reflects human influences as much as fundamental stand dynamics (McLachlan et al. 2000). Thus, the contemporary view emphasizes the multiple pathways and rates by which old-growth ecosystems can develop (Donato et al. 2012; Halpin and Lorimer 2016; Urbano and Keeton 2017). Site productivity (soil fertility, local climate, aspect, etc.) and well as the type, intensity, and timing of disturbance events exert major influences on these developmental trajectories. This is a critical lesson for old-growth silviculture because the targets are not fixed: They are a continuous range of stand structural conditions, responding dynamically to their environment over time and space. Old-growth silviculture must work with, not against, these dynamics, manipulating stand development processes to achieve the desired ecosystem functions—like structurally complex habitats and carbon storage—but recognizing that continuous, sometimes unpredictable, change is certain (Fahey et al. 2018).

Consequently, there is no one-size-fits-all approach, but rather a range of possibilities that must be tailored to the stand or property-specific management objectives, disturbance regimes, land-use history, and site conditions. The idea of natural variability in old-growth structure and function was described further by Bauhus et al. (2009). They endorsed the concept of a range of "old-growthness," arguing that simple structural criteria or age thresholds fail to capture the dynamics of natural baselines or variation in the values of any one parameter, such as large tree density or downed coarse woody debris, in late successional forests. This conclusion was supported by the global review of old-growth structure performed by Burrascano et al. (2013). They found a wide range of variability around mean values for parameters, such as large tree density, downed woody debris volumes, and basal area, within both mature and old-growth age classes in temperate forests worldwide, including parts of the eastern United States. In some cases, structural characteristics typically associated with old growth may be equally, if not more, pronounced in mature forests, depending on site characteristics and disturbance history (Burrascano et al. 2013). This suggests a need to broaden our concept of late successional dynamics and to move away from overly narrow or rigid classification criteria. Therefore, it follows that targets for old-growth silviculture are a continuum of possibilities rather than a discrete or uniform set of objectives.

Principles of Old-Growth Silviculture

Depending on landholding and management objectives, management for old growth may or may not involve the harvesting and removal of trees for wood products. In some cases, such as in natural areas or parklands, if any trees are felled, they are often left to decay on site. On other ownerships, silvicultural treatments in zones with active forest management may be selected to enhance or accelerate the development of old-growth structural features, with some trees being removed to help defray the costs of restoration. Another option for forest landscape managers is to designate "aging areas" where extended rotations or no-harvest inclusions might be employed to increase the variety of old-growth stand features (Mladenoff et al. 1994). In the eastern United States, these areas of active forest management are second- or third-growth forests, not remnant fragments of the original old growth in natural areas.

Given that old growth continuously changes in species and structure, managers should avoid establishing a static management target, reflecting the older conception of old growth as a single, homogeneous stage of development. In late successional forests of shade-tolerant tree species, such as spruce-fir and hemlock-northern hardwoods, foresters were long accustomed to establishing a structural goal for uneven-aged stands in which the residual size distribution after harvest resembles a negative exponential or "reverse J-shaped" curve (O'Hara 1998). This made sense as a means of ensuring sustainable harvests under the selection system (Crow et al. 1981). It would be easy to extend this concept to old-growth management simply by increasing the maximum residual diameter and stand basal area.

However, as has already been shown for conventional single-tree selection, this approach, if applied too broadly, lowers species diversity and stand heterogeneity because of the small and uniform gap sizes (Della-Bianca and Beck 1985; Leak and Sendak 2002; Schuler 2004). Applying this management target for old growth would imply that small gap dynamics are the only important disturbance process to mimic with old-growth silviculture. Although unforeseen natural disturbances in managed stands can maintain some of this heterogeneity, foresters should recognize that a wide range of structural conditions and disturbance histories are represented in old growth, including unimodal size distributions and two- or three-aged stands. On intact old-growth northern hardwood landscapes in Michigan, only about half of the old-growth stands approach a descending monotonic size distribution (i.e., vertically continuous canopies), with the remainder represented by unimodal or bimodal distributions (Lorimer and Halpin 2014). There is evidence that stands with a unimodal distribution (i.e., limited understory development) are ecologically important for some organisms. For example, the dense understory and numerous sapling gaps in the archetypal all-aged stand can be an obstruction when goshawks (*Accipiter gentilis*) forage beneath the canopy or when forest bats sense such environments as being filled with obstructions (Owen et al. 2004; Boal et al. 2005).

Multicohort management that maintains some uneven-aged stands with a variety of opening sizes can help create conditions that enable perpetuation of mid- and shade-intolerant tree species as a component of the stand, either through natural regeneration, planting, or both. Gap size is only one of several important factors affecting the recruitment and growth of the less shade-tolerant species. Therefore, ancillary treatments may be needed, especially on better sites affected by novel stressors (Bolton and D'Amato 2011; Kern et al. 2013; see further discussion below). Multiple-tree gaps are usually needed to ensure successful recruitment into the canopy before lateral closure occurs (Runkle and Yetter 1987; Leak 1999; Webster and Lorimer 2005). These gaps can be installed as group selection openings or as larger openings (up to roughly 0.5 hectares or more) in the context of an irregular, multicohort harvest removing about 40 to 50 percent of the stand basal area (Leak 1999; Hanson and Lorimer 2007; Hanson et al. 2012). Managers should be careful, however, not to overcompensate and create too many large openings. Heavier multicohort harvests probably need to be undertaken only once or twice during the entire 250-year life span of a cohort to mimic natural processes and accomplish ecological objectives. A temporary shelterwood overstory may also be needed in larger openings to hinder the development of dense shrub layers. Similar cautions about gap size and shrub competition apply to group selection (Kern et al. 2013; Walters et al. 2016). Furthermore, simulation studies have suggested that a high degree of smallscale forest fragmentation can occur if groups occupy 9 percent or more of the forest matrix in each cutting cycle (Gustafson and Crow 1996; Halpin and Lorimer 2017). Excessive lateral crown exposure could conceivably create additional physiological stress on residual trees under a warming climate.

Pioneer tree species, such as the pines (*Pinus* spp.), present much different management challenges compared to the shade-tolerant species. Maintaining an age-class mosaic is easier on public lands managed for multiple objectives, such as state and national forests in the United States or provincial forests in Canada, than in reserves, because conventional silvicultural methods (e.g., clear-cutting with reserves and irregular shelterwoods) can be used to establish the younger stands. However, the eventual replacement of old pioneer trees by shade-tolerant species will at some point require their conversion to younger stands if the proportion of old growth on the landscape is to remain stable at a level agreed upon in policy negotiations.

One of the greatest areas of interest in old-growth silviculture has been the idea of emulating the effects of natural disturbances on rates and pathways of forest development, with the intent of accelerating rates of old-growth structural and compositional development (North and Keeton 2008). Broadly defined, natural-disturbance based silviculture incorporates biological legacies (e.g., carryover of organically derived structures) into prescriptions. This emulates stand development processes, including small-scale disturbances, in intermediate treatments (i.e., thinning) and allows for appropriate intervals between regeneration harvests, known as *rotation periods* or *entry cycles*, for recovery of late successional habitats (Seymour et al. 2002; Franklin et al. 2007). Thinning, as a form of stand improvement, has been used for years as a method to more rapidly move stands into later stages of development. But, while conventional thinning increases growth increments on residual trees, it can also have the disadvantage for old-growth silviculture of simplifying some attributes of stand structure if employed too aggressively. This is particularly true if applied through spatially uniform timber marking and when less vigorous or defective trees are the main removals, which can substantially reduce the potential for dead tree recruitment. For this reason, concepts like variable density thinning—encouraging horizontal heterogeneity within stands—and deliberate retention of a component of dead, dying, and defective trees offer useful alternatives for intermediate treatments.

A variety of methods employed in conjunction with either intermediate treatments or regeneration harvests are also relevant. Management for old-growth conditions—often synonymous with management for structural complexity at the stand level in moist to wet temperate forests—can include a broad array of techniques used in tandem or individually, depending on stand conditions and the desired mix of cobenefits. Some foresters might even reject the notion that treatments must be strictly defined as either intermediate or regeneration harvest (Franklin et al. 1997). If natural disturbances can free up growing space, thereby enhancing growth in residual trees while regenerating a new cohort of trees, then so might hybrid, disturbance-based forestry practices (Keeton 2006). When variations of selection systems or multicohort management are used for old-growth objectives, oft-cited techniques include residual diameter distributions of variable forms, large tree retention, crown release around dominant and codominant trees, girdling to create dead trees (snags), enhancement of downed coarse woody debris, variable density thinning or tree selection, and creating variably sized, irregularly shaped harvest gaps (sometimes including within-gap legacy tree retention) (O'Hara 1998; Keeton 2006; North and Keeton 2008; Kern et al. 2016). For each, the forester must carefully consider both the baseline referenced in developing the silvicultural prescription, the dynamics of that baseline over time and space (since no baseline is truly stable), and how the technique will work with, and ideally accelerate, stand development processes, such as gap formation, understory reinitiation (i.e., regeneration) of mid- and shade-tolerant species, vertical differentiation of the canopy, tree growth across all canopy strata, and dead wood recruitment. Old-growth silviculture in eastern deciduous, coniferous, and mixed-wood forests, therefore, is like a tool box with multiple options the forester might consider, rather than a single approach. If there is a unifying theme, it is that old-growth silviculture should emulate and promote a range of stand development processes, including those induced by both self-thinning and natural disturbance effects.

Experimentation: Can We Restore Elements of Old-Growth Structure and Function?

The idea of managing eastern forests for old-growth characteristics is no longer theoretical. Rather, experimental research over the last 20 years has clearly established the ability of carefully planned silvicultural interventions to enhance developmental rates for late successional structure, function, and composition. For example, to address the problems of low species diversity under single-tree selection, a number of field trials across the northern hardwood region have examined the effects of harvest-created openings on natural or planted seedlings of mid- or shade-intolerant tree species (Leak 1999; Webster and Lorimer 2005; Kern et al. 2012, 2013; Bolton and D'Amato 2011; Fahey and Lorimer 2013; D'Amato et al. 2015; Gauthier et al. 2016; Gottesman and Keeton 2017). Several broad conclusions have been reached. First, successful long-term recruitment into the canopy is not very likely in openings smaller than 180 to 200 square meters because of low light intensities and lateral crown encroachment from gap border trees. Also, in the case of white pine, openings may need to be considerably larger to reduce infection by white pine blister rust (*Cronartium ribicola*), which is aggravated by cold-air drainage in small openings. Second, success varies widely among habitats. On the richer habitats, competition with shrubs and taller saplings of shade-tolerant species is often so severe that survival of the mid-tolerant species is very low and growth of survivors is slow. Success is more likely on sites of moderate or below-average productivity. Success on better sites may require control of understory competition, scarification of the soil surface, and retention of fallen woody debris. Third, in areas of moderate to high deer densities, special measures may need to be taken to reduce losses from browsing, such as repeated application of deer repellants to terminal leaders. Fourth, preliminary evidence suggests that natural regeneration is often more vigorous and faster growing than planted seedlings, perhaps because of physiological stress in planted stock. Future improvements in planting stock, and perhaps improvements in containerized seedlings, may help remedy these problems.

Field studies have also evaluated the use of silvicultural treatments to hasten the development of old-growth structural features. A comparison of managed second-growth and unmanaged old-growth northern hardwood stands showed that the proportion of the canopy in openings and the gap size distribution were very similar in both management types. This was the case even though the harvests in second growth were conventional single-tree selections and were not intentionally designed to mimic old-growth processes (Goodburn 1996). In contrast, a comparison of canopy dynamics in Quebec, Canada, characterized with multitemporal LiDAR data, indicated the need for a recovery period of at least 20 years after selection cutting before canopy dynamics returned to something similar to the referenced old-growth deciduous forest (Senécal et al. 2018). The Quebec study concluded that, under a selection cutting cycle of 25 years, forest canopy dynamics will be distinctly different from old-growth forests for 80 percent of the harvest rotation period or entry cycle. Similarly, in a study of gap dynamics in old-growth hemlock-hardwood forests, Curzon and Keeton (2010) found that the canopy openings were not only larger, on average, than those documented for young and mature forests, but also irregularly shaped and variably sized, with ragged within-gap structure related to the abundance of legacy trees, both live and dead. A challenge for silviculture, therefore, is to emulate this tremendous variability in gap structure and canopy architecture associated with natural disturbance effects in old, unmanaged forests.

In principle, canopy gaps, snags and logs, and multilayered vegetation are elements of old growth that should be possible to restore fairly quickly in second-growth stands by silvicultural treatments. A study in Pennsylvanian oak forests, for example, showed that retention of cull trees and snags in stands during improvement cuts was successful in elevating bird abundance compared to stands with conventional treatment (Stribling et al. 1990). Designing structural enhancement treatments begins by comparing the habitat elements already provided in conventionally managed forests with those found in old-growth forests. For instance, total coarse woody debris volumes under conventional single-tree selection can range from about 50 to 70 percent of the volumes in unmanaged old growth (Hardt and Swank 1997; Goodburn and Lorimer 1999; McGee et al. 1999; Doyon et al. 2005). Harvest treatments designed to restore old-growth structural elements in Vermont northern hardwood-conifer forests resulted in downed log volumes about 88 percent of old-growth volumes and 50 to 100 percent greater than usually achieved in conventional single-tree selection (Keeton 2006). Mixed results have also been observed. In a recent largescale experiment, using commercial harvest to enhance old-growth features in Wisconsin, damage during harvesting and subsequent mortality reduced the retention of small preexisting snags. More surprising was that net density of standing snags larger than 25 centimeters DBH was not significantly increased five years after girdling 5 trees per hectare—a treatment that was intended to boost snag density (Fassnacht and Steele 2016).

The question of whether silvicultural treatments can accelerate the development of large trees was recognized at the outset as a more uncertain proposition. Canopy trees in second-growth stands are already vigorous, fast-growing trees receiving direct sunlight at the top of the crown and, in many cases, are 80 to 100 years old. Would thinning the canopy actually boost growth rates in vigorous and relatively old trees that are beyond the age at which thinning is usually conducted? At least for the shade-tolerant sugar maple (*Acer saccharum*), the answer may be yes. A retrospective field study of thinned stands indicated that substantial mean basal area growth increases of 74 to 107 percent occurred even in canopy trees more than 100 years old. The response, moreover, was proportional to the degree of crown perimeter exposure (Singer and Lorimer 1997). Simulations based on these field data suggested that the time required for a 77-year-old northern hardwood stand to reach minimum structural criteria of old growth could be reduced from 79 years to 36 years after a series of three moderate thinning treatments at 15-year intervals (Choi et al. 2007). Size distributions after 45 years resembled those of stands in the later stages of old growth. An important caveat was that, if the stand being treated was already uneven-aged with some large trees, aggressive thinning treatments could actually increase the amount of time required to reach minimum old-growth structural criteria, because some medium and large trees had to be cut to meet the targeted thinning intensity. Thinning caused little change to coarse woody debris volume when 20 percent of cut-tree volume was left on site and 80 percent was removed, but a higher proportion of coarse woody debris was in larger size classes on the treated sites.

In the northern hardwood region of the northeastern United States, one of the first experimental tests of old-growth silviculture evaluated an approach called Structural Complexity Enhancement (SCE) that was compared alongside conventional single-tree and group-selection harvests (figure 13-2; Keeton 2006). The study, started in 2001, is replicated at two research forests in northern Vermont and employs many of the individual

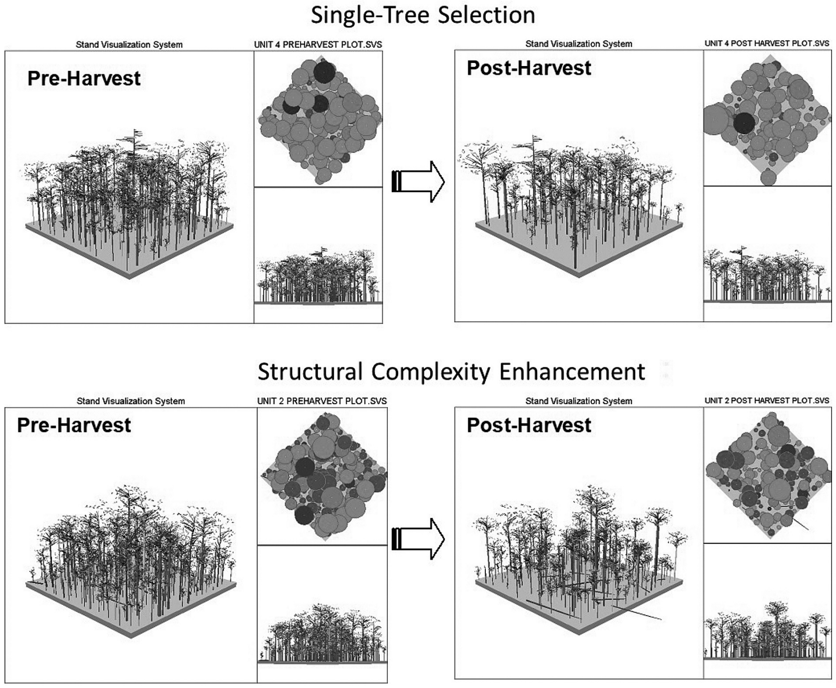

FIGURE 13-2. Visualizations using field data and contrasting 0.01-hectare sample plots in single-tree selection (above) and Structural Complexity Enhancement (SCE) treatments (below). The plots are part of an old-growth silvicultural experiment located on the Mt. Mansfield State Forest in Vermont. Tree coloration is species-specific, with plots seen from oblique, aerial, and side profile views. Differences between these immediately postharvest outcomes are subtle but note the high degree of postharvest structure (e.g., basal area and stem density), vertical complexity, and downed log densities in the SCE plot. Note also the somewhat lesser structural retention for single-tree selection, as well as the lack of downed logs and lower spatial variation in tree density.

techniques described above, but these methods were used jointly to accelerate development of multiple-stand structural characteristics (table 13-1). One of the innovative aspects of the study was a test of an alternative diameter distribution called a “rotated sigmoid” as the postharvest target. Sigmoidal form is one of several possible distributions in eastern US old-growth forests (Goodburn and Lorimer 1999). Although discussed in the theoretical literature (O’Hara 1998), the distribution had not previously been field tested as a way to shift growing-space allocation and, potentially, aid in the recruitment of large trees over time. To determine if SCE was

Table 13-1. Silvicultural prescriptions for treatments compared against an old-growth approach, called Structural Complexity Enhancement (SCE), developed for northern hardwood-conifer forests in northern New England, as described in Keeton (2006) and Ford and Keeton (2017). To make it a “fair” test, the study compared SCE against conventional selection systems modified to retain more structure, particularly in medium and larger tree size classes, than is typical in the region. The target basal area (postharvest for selection treatments; desired in the future for SCE), maximum tree diameter retained postharvest (selection treatments) or desired in the future (SCE), and q-factor define the shape of the residual (or postharvest) diameter distribution. For SCE, the variable q-factor approximated the rotated sigmoid distribution sometimes found in old-growth forests. The conventional treatments employed negative exponential distributions. Table modified from Ford and Keeton (2017).

Target residual basal area (m^2 ha^{-1})	*Max diameter (cm)*	*q-factor**	*Structural objective*	*Silvicultural prescription*
Treatment: SINGLE-TREE SELECTION				
18.4	60	1.3	Structural retention	• Modified residual basal area and diameter distribution
			Vertically differentiated canopy	• Released advance regeneration • Regenerated new cohort
Treatment: GROUP SELECTION				
18.4	60	1.3	Structural retention	• Modified residual basal area and diameter distribution
			Vertically differentiated canopy	• Released advance regeneration • Regenerated new cohort
			Horizontal diversification	• Spatially aggregated harvest (patches ~0.05 hectare)
Treatment: STRCTURAL COMPLEXITY ENHANCEMENT				
34.0	90	2.0/1.1/1.3	Reallocated basal area to larger size class	• Rotated sigmoid diameter distributions • High maximum diameter and target basal area • Retained trees >60 centimeters DBH
			Vertically differentiated canopy	• Released advance regeneration • Regenerated new cohort

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TABLE 13-1. *continued*

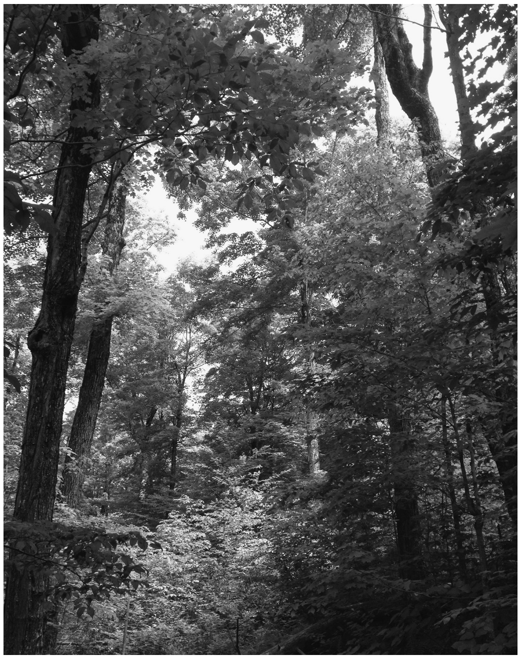
Target residual basal area (m^2 ha^{-1})	*Max diameter (cm)*	*q-factor**	*Structural objective*	*Silvicultural prescription*
Treatment: STRCTURAL COMPLEXITY ENHANCEMENT				
34.0	90	2.0/ 1.1/ 1.3	Horizontal diversification	• Marked trees for variable density • Created small gaps (~0.02 hectare) around crown-released trees
			Dampened growth decline in larger trees	• Enabled full (3- or 4-sided) and partial (2-sided) crown release
			Elevated coarse woody material volume and density	• Girdled trees to create snags • Felled and left trees to create downed logs • Pushed or pulled trees over to create tip-up mounds

* q-factor is the ratio of the number of trees in each successively larger size class

successful, investigators tracked various indicators of stand development, financial viability, late successional biodiversity, tree regeneration, and aboveground carbon pools.

As confirmation of the effectiveness of crown release (see above) and possibly the rotated sigmoid residual diameter distribution, as techniques to enhance the representation of large trees, computer model simulations predict that the stands treated with SCE are likely to develop an average of 5 more large trees (greater than 50 centimeters DBH) per hectare than there would have been without treatment after 50 years. This contrasts with the conventional treatments, where simulations project 10 fewer large trees per hectare on average than would recruit in the absence of timber harvesting (Keeton 2006). Furthermore, an exciting outcome of this work has been finding that SCE can produce carbon storage cobenefits while simultaneously achieving late successional habitat objectives (Figure 13-3). In fact, ten years after harvest, measured aboveground carbon in SCE units had recovered to only 15.9 percent less than simulated no-harvest baselines, compared to 44.9 percent less in conventional treatments (Ford and Keeton 2017).

While all the treatments were generally successful in maintaining the overall richness and/or abundance of understory plants, terrestrial sala-



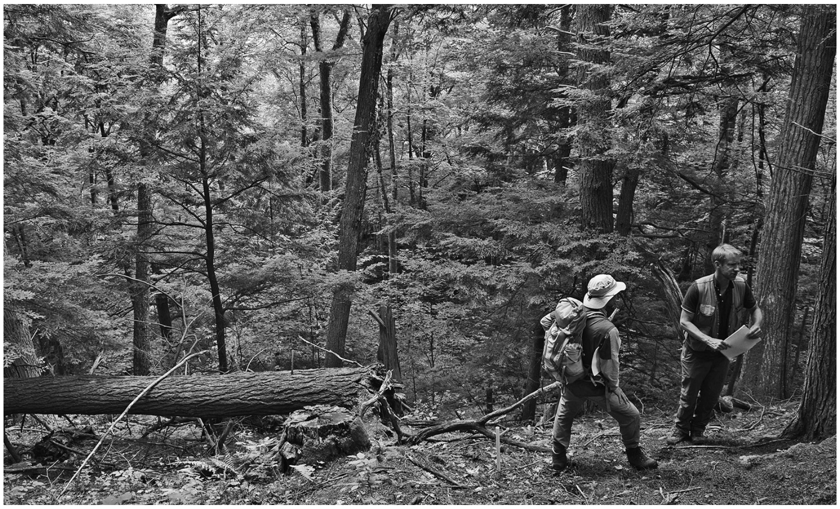


FIGURE 13-3. The outcome of Structural Complexity Enhancement at a northern hardwood forest 13 years after treatment (top) and in a mixed-woods forest 15 years after treatment (bottom). Both locations are in Vermont, USA. Note the successful development of large trees, canopy differentiation, high levels of aboveground biomass, and other elements of old-growth-like characteristics. Photo credits: W. S. Keeton (top), R. Aszalós (bottom).

manders, and fungi, the diversity of sensitive, late successional, herbaceous plants increased significantly under SCE and decreased significantly in the semiopen canopied conditions within group-selection treatments (McKenny et al. 2006; Smith et al. 2008). Importantly, the understory plant responses were strongly affected by overstory treatment and less influenced by soil chemistry and drought stress. Fungi and salamander responses were strongly associated with microsite characteristics, particularly silviculturally enhanced snag and downed log densities, and increased significantly under SCE, but showed no significant decrease in relatively small gaps (0.05 hectares in size on average) created by group selection (Dove and Keeton 2015). Fully established tree regeneration 13 years after both SCE and the selection harvests was spatially variable (or patchy) but sufficient to maintain desirable stocking and a diverse species mix. However, as many foresters in the northern hardwood region have experienced firsthand, the problem of competition between seedlings and saplings of more commercially desirable species and beech sprouts was a limitation of all these relatively low impact treatments, particularly group selection, and may require active beech control in the future (Gottesman and Keeton 2017).

Managing for old-growth characteristics takes on a different spin in forests with natural disturbance regimes best described as canopy-replacing. In these forests, the silvicultural approach of variable-retention harvesting (VRH) is being used to emulate a key aspect of natural disturbance, specifically retaining biological legacies from the pre- to post-disturbance forest (Franklin et al. 2007). Broadly speaking, biological legacies are defined as organisms, organic materials, and organically derived patterns in soil and vegetation that persist from the pre-disturbance ecosystem into the post-disturbance environment (Franklin et al. 2007).

In practice, legacy management often focuses on structures that enrich the new forest simply because they are large, including live and dead trees (snags) and logs on the forest floor, as well as patches (aggregates) of intact forest. VRH, when used for the purpose of legacy management, addresses the ecological principle of *continuity*—maintaining elements of structure, function, and biota from the original forest during regeneration harvesting (Palik and D'Amato 2017).

Beyond the obvious habitat value of large structures, there is the practical consideration that *large* generally equates to *old*; that is, these structures often take decades or centuries to develop. Thus, VRH, for structural enrichment, focuses on leaving some of the largest structures available at harvest, potentially in perpetuity in the case of live trees; that is, these trees are left to live out their natural life spans and ultimately transition into the snag and downed-log pool. VRH, for structural enrichment, is used globally (Gustafsson et al. 2012). In the eastern United States, it has been used most extensively in the northern Great Lakes region, particularly in pine- (*Pinus*) and aspen- (*Populus*) dominated forests (e.g., Palik and Zasada 2003; Klockow et al. 2013).

The first operational-scale application of VRH in the Lake States was in red pine forests of the Chippewa National Forest in northern Minnesota (Palik and Zasada 2003). This largescale management experiment was designed to evaluate ecosystem responses to dispersed and aggregated retention of pines, which were left in a harvested matrix that was regenerating to mixtures of pines, oaks (*Quercus*), and boreal hardwoods, a composition better reflective of the native ecosystem. An important finding of this work was that the spatial pattern of retention can be manipulated across stands so as to favor tree species of differing shade tolerances, depending on regeneration objectives. Moreover, reduction in resource availability to regenerating seedlings attributed to competition with retained pines can be minimized by concentrating reserve trees in groups surrounding openings. The practical application of these findings was that large, legacy trees can be maintained to structurally enrich the new forest, without greatly compromising new cohort growth (Montgomery et al. 2013). While VRH approaches are not old-growth silviculture in the traditional sense (nor as described earlier in this chapter), their use in forests actively managed for timber products, traditionally using even-aged methods, does represent a strategy for maintaining and enhancing structural elements characteristic of old forests.

Adaptive Old-Growth Silviculture

A frequent criticism of old-growth forest restoration reflects the concern that this may be increasingly irrelevant in a rapidly changing world. There is the legitimate skepticism a) of whether historical baselines are still relevant in the context of global change, including climate change, biodiversity loss, invasive species, and atmospheric deposition of pollutants; and b) of whether late successional and old-growth forests will be adaptive to future shifts in disturbance regimes, potential loss of foundational species, and the needs of growing human populations. With species range shifts and the probable formation of novel species assemblages in the future—as occurred with past climate changes—managing for compositional baselines inferred from remaining primary forests or reconstructed through other methods (e.g., Cogbill et al. 2003) may no longer be appropriate. While managing for historical baseline composition overall is likely problematic, it still may be important to determine if any of the tree species that are part of the old-growth mix, even if occurring in low abundance, may be future-climate adaptive. This addresses the often cited first line of defense against climate change, specifically, maintaining tree species diversity in managed forests (e.g., Brang et al. 2014). In this context, one or more species in the ecosystem may be future-climate adaptive, so consideration should be given to increasing, maintaining, or restoring their abundance to provide the option to increase the numbers of these species in the future (Messier et al. 2013). Alternatively old-growth compositional objectives would need to track or anticipate range shifts, a difficult proposition at best. Furthermore, with the spread of invasive pests and pathogens and loss of foundational species such as the eastern hemlock (*Tsuga canadensis*) and species-specific structures like large, old American beech (*Fagus americana*), foresters may be working with increasingly simplified systems. And if disturbance intensities and frequencies increase (Diffenbaugh et al. 2013), old-growth structure may be particularly vulnerable on disturbance-prone sites. All these uncertainties beg the question, Are we trying to manage for the forest of the past rather than for the forest of the future?

And yet, it is reasonable to propose that managing for old-growth characteristics could also be a part of an adaptation strategy based on enhancing the resilience and the resistance properties of a landscape (D'Amato et al. 2011). Recent advances in adaptive silviculture have applied the science of complex systems to questions about how to manage for resilience to natural and anthropogenic stress. As pioneers in this field, Millar et al. (2007) proposed a three-pronged framework to guide adaptive silviculture: 1) resistance for forestalling impacts and protecting highly valued resources, 2) resilience for improving the capacity of ecosystems to return to desired conditions after disturbance, and 3) response for facilitating transition from current to new conditions. We wonder if elements of structure and function associated with old-growth may be more resilient to change than is species composition. Old-growth forests could certainly be considered complex adaptive systems (Messier et al. 2013; Fahey et al. 2018). For example, if shifting late successional species assemblages are nevertheless able to maintain high levels of carbon storage or to provide critical habitat elements, such as large snags, downed logs, gap environments, and tip-up mounds, then some structure-function relationships will be maintained. Biodiversity using such habitat elements will still need these structures in the future, even if the tree species providing these structures changes, assuming some degree of plasticity in these relationships, which is certainly not always the case. In this sense, managing for old-growth structure, could help functional processes recover from or accommodate compositional transitions. Moreover, the complex canopies of old-growth forests buffer below-canopy microclimates from fluctuations in climatic influences. This adds ecological resistance to changes occurring above the canopy and has been shown to help biodiversity persist in the face of warming conditions (Frey et al. 2016).

Managing for old-growth characteristics, as reflected in structural, compositional, and functional diversity of these stands, may well provide the flexibility needed to shift or transition forest development in different directions as evolving climate conditions warrant. This kind of diversification is akin to the concept of a diversified financial investment portfolio but applied to forest adaptation. A greater range of investment options better insures ability to adapt to changing market conditions. There is also interest in preferentially managing for certain groups of species based on functional traits that confer either resilience or resistance to disturbances and stress (Aubin et al. 2016). This approach complements old-growth silviculture quite well, as the latter typically entails variants of partial cutting that can incorporate preferential retention of species exhibiting adaptive functional traits.

In short, we remain optimistic that old-growth will not only have a place on the future landscape but will continue to provide important ecosystem services and essential habitat functions. But realizing this future will require a combination of protected-area strategies and silvicultural practices that are adaptive to change, particularly in terms of species composition, invasive species, and altered disturbance regimes.

Conclusion

Old-growth silviculture in eastern North America has come a long way in the last couple of decades, developing from a largely theoretical proposition to an experimentally tested and operationally vetted endeavor. We have learned that old-growth baselines developed from primary (never cleared) forests are highly variable because of the formative role of disturbance histories and complex successional dynamics in shaping those systems. This means that desired future conditions may also encompass a range of possibilities. Moreover, there is no strict code for what it means to manage for old-growth characteristics. Targets, and the specific techniques employed to achieve them, can be tailored to site conditions and to suit landowner objectives and the desired mix of cobenefits, both timber and nontimber. For example, some degree of coarse woody debris retention or enhancement is easily incorporated into most harvesting systems with minimal trade-offs in terms of foregone timber yield. Other specifics, such as more complex prescriptions involving the form of post-harvest diameter distribution or even tip-up mound creation, may or may not be used, depending on landowner interest or operational feasibility. Multicohort or irregular shelterwood systems, such as "expanding gap" systems incorporating permanent retention of legacy trees, are not only well tested (Raymond et al. 2009; Kern et al. 2016) but of increasing use operationally for a variety of objectives, including certain types of bird habitat (Hagenbuch et al. 2013). But these systems should comprise just one component of the overall efforts to diversity stand structures and enhance complexity at landscape scales since multicohort systems do not produce the full range of late successional forest conditions.

Given this inherent flexibility in silviculture oriented toward old-growth, a variety of practical applications present themselves. These range from full-fledged, old-growth restoration—for instance in nature reserves—to habitat provision within managed forests, to carbon forestry focused on promoting high stocking and high levels of biomass, to carefully planned, and probably more limited, interventions in riparian areas to enhance late successional, forest-stream interactions, including flood resilience. Choice of application will determine the appropriate rotation period or entry cycle, the number of harvest entries (e.g., one time only or on-going), and the degree of old-growth structure ultimately developed (see table 13-2). For instance, for restoration purposes in a nature reserve, managers might prefer a single entry, with stand development processes allowed to take over thereafter. In most "improved forest management" carbon applications, landowners generally favor on-going, active timber management, so long as it maintains the high levels of stocking encouraged by existing carbon market protocols. In the former, we might expect the full array of old-growth characteristics to develop over time, whereas in the latter, perhaps only some of these will develop and possibly to a lesser degree.

Clearly silviculture promoting the characteristics of old-growth forests can contribute to biodiversity conservation and terrestrial carbon storage in eastern forest ecosystems while providing both timber and nontimber economic opportunities. Active management for this purpose will complement strategies of protected-areas and can comprise one element of adaptive management (Keeton 2007). In the course of their professional careers, the authors of this chapter have seen growing accep-

Table 13-2. Examples of applications of old-growth silviculture, varying management objective, number of harvest entries, and degree of expected late successional structural development.

Application	*No. of Entries*	*Late Successional Structural Development*	*Carbon Storage Emphasis*
Old-growth restoration	One or possibly two entries	High	High
Riparian management	Single or multiple	Moderate to high	Moderate to high
Timber emphasis	Multiple	Low to moderate	Low to moderate

tance of old-growth silvicultural concepts and expanding application in a variety of contexts across a range of forestland ownerships—public and private. With continued experimentation and demonstration, the future looks bright for old-growth silviculture as a tool applicable to both restoration and integrated management on working forests, provided concepts of late successional forest structure and function can adapt to changing environmental-boundary conditions.

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