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Chapter 4

Old-Growth Forests in the Southern Appalachians: Dynamics and Conservation Frameworks

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In the southern Appalachian Mountains, compositions, structures, and dynamics of forest communities vary across steep topographic gradients, such as elevation and slope aspect, position on slope, steepness, and slope shape (Whittaker 1956). For instance, in mesic sites, the forest transitions across elevations from lower elevation cove hardwoods and hemlock forests to higher elevation northern hardwoods and, where the mountains surpass approximately 1,680 meters, spruce-fir forests. At mid and low elevations, cove forests on protected sites transition to oak-dominated forests on drier soils and finally to pine and xeric hardwood forests on exposed south- to west-facing sites. Despite a long history of human influence, remnant old-growth forests have survived across these landscape gradients and now comprise, in aggregate, one of the largest totals for old-growth acreage in eastern North America (Davis 1996).

We have three goals in this chapter: to describe the natural and human disturbances that have shaped old-growth forests in this region; to describe the structural variation of old-growth forest in Great Smoky Mountains National Park, using remarkable datasets from the 1930s and 1990s; and to present a framework for evaluating, delineating, and conserving these forests. The 1930s dataset shows forests at the start of chestnut blight and just prior to the time when fire suppression was becoming effective (MacKenzie and White 1998). The 1990s dataset is after balsam woolly adelgid and beech bark disease introduction, but before arrival of the hemlock woolly adelgid. In a concluding section, we discuss the implications of these dynamics for the delineation and future of old-growth forests in the high mountain southern Appalachians or southern Blue Ridge region (Davis 2000).

Old Growth and Human and Natural Disturbances

Historically, the southern Appalachians supported diverse forest communities with trees of impressive age and size. On mesic mid- and low-elevation sites, trees sometimes exceeded 400 years, 3-meter diameters, and 60-meter heights. Naturalist William Bartram explored the mountains in the late 1700s. The tone of his account displayed astonishment at the magnificence of the forests (Bartram 1791). Bartram also described human impacts, including Native American villages and agriculture fields on the productive soils along rivers and streams and in open forests, plains, and cane breaks that Native Americans likely managed with fire. Though old-growth forests covered much of the landscape outside settled areas, charred wood from fire pits shows that firewood gathering could deplete the highest quality hardwood species from forests surrounding Native American villages (Delcourt 1987).

Beginning in earnest about 1800, European settlers replaced declining Native American populations and expanded or reestablished agriculture on valley flats and lower mountain slopes. These settlers also introduced cattle, sheep, and pigs, increased harvest for timber and fuel, and continued the use of fire. However, the most dramatic transformation of southern Appalachian forests was caused by widespread and unregulated corporate logging that began in the late 1800s and continued until about 1930, even as advocates of conservation and more scientific forestry practices were instituting protective measures. The most exploitive phase of logging extended from the lowest to the highest elevations and sometimes was followed by severe slash fires and soil erosion. Some sites with severe soil erosion still lack complete tree cover 80 to 100 years after logging.

Just before the most intense logging, Ayers and Ashe (1905) completed a forest survey to assess timber in western North Carolina and eastern Tennessee. They reported average tree ages between 104 and 221 years, thus dating these forests to before European settlement of these lands. However, the landscape was quite varied. At one end of the spectrum were forests around settled areas, where logging, land clearing, and fire were extensive. At the other end of the spectrum, in areas far from railroads (at the time), logging impacts were absent or targeted only high-value trees, and "some remarkable fine timber trees" (Ayers and Ashe 1905) still made up the relatively unbroken forest. Areas of older forest included the north slope of the Great Smoky Mountains, where old growth remains today. Logging impacts eventually slowed and became less severe with creation of six national forests, an effort made possible by passage of the Weeks Act in 1911, as well as the establishment of Great Smoky Mountains National Park, authorized by Congress for land purchases in 1926 and established as a park in 1934. The legacy of logging means that today's landscape is largely covered by second-growth forests of relatively uniform ages, with a dearth of both old-growth and early successional habitats (Greenberg et al. 2011). Remnant sites escaped logging and settlement for a variety of reasons, including presence on steep, high elevation, less accessible, and less commercially viable sites. Thus, remnant old-growth forests are a nonrandom sample of the original landscape.

Remaining Old Growth

How much old growth remains in the southern Appalachians? This question is hard to answer with precision for three reasons: First, it depends on the criteria used to delineate old growth (a subject we develop more fully below); second, there are problems in accurately documenting past human disturbance on some sites; and, third, the forests, even when not subject to logging or settlement, are continuing to change because of natural and indirect human disturbances. Despite these issues, it is estimated that more than 100,000 hectares of old-growth forest remain in the southern Appalachians (Pyle 1985; Johnson 1995; Messick 2004).

Great Smoky Mountains National Park protects about 43,900 hectares of old-growth forest defined as areas that were not logged or farmed (Pyle 1985; as modified in Tuttle and White 2016). Pyle (1985) mapped an additional 59,400 hectares of "diffuse disturbance" areas with milder human impacts such as selective logging, fire, and grazing. Outside Great Smoky Mountains National Park, Messick (2004; Yost et al. 1994; Johnson 1995) used lack of human disturbance and tree age to define three categories for old-growth delineation: A. no sign of human disturbance, trees older than150 years; B. many trees older than150 years, but evidence of such disturbance as chestnut blight (one might add other invasive forest pests—see below) or culling more than 50 years ago OR no sign of human disturbance but trees younger than 150 years, probably due to natural disturbance; and B+. larger tracts that had a mix of characteristics of categories A and B. In these three categories, Messick (2004) compiled documentation for 43,500 hectares of old-growth forest on six national forests, comprising 4.5 percent of those public lands, with an additional 190 hectares on private lands. Messick (pers. comm.) has also noted that additional old-growth forests have been documented since his 2004 compilation and that an updated old-growth catalog is much needed to delineate old growth on national forest land.

Some of the forests in Great Smoky Mountains National Park labeled as "diffuse disturbance" (Pyle 1985) contain areas that would qualify as old growth under Messick's definition—areas with minor logging effects ("culling") but no settlement. In one attempt to bridge the gap between Messick's and Pyle's categories, Johnson (1995; see also Yost et al. 1994) estimated 60,700 hectares of old growth in Great Smoky Mountains National Park (versus Pyle's 43,900 hectares without logging or settlement), which would bring the regional total to 105,900 hectares. Clearly, a consistent evaluation of old growth in the southern Appalachians is needed, given the importance, uniqueness, and future impacts to these forests.

Ongoing Natural and Human Disturbances in Old-Growth Forests

The remnant old-growth forests in the southern Appalachians are now—and have always been—subject to a range of natural disturbances (Harmon et al. 1983; White et al. 2011). Smaller disturbances, such as single tree falls, usually lead to minor if any changes in forest composition, but large ones can initiate succession, thereby producing structural and compositional variation. In the case of smallscale gap dynamics, dendrochronological studies have shown that old-growth forests have repeated patterns of suppression and release of tree growth (Di Filippo et al. 2017). Kincaid and Parker (2008) reported that release events that caused at least a 50-percent increase in growth in old-growth hemlock forests in Great Smoky Mountains National Park occurred with a frequency of 0.48 per year per tree. Busing (2005) reported mortality rates for trees of less than 10 centimeters in diameter at breast height of 0.5 to1.4 percent per year. Runkle (1985) reported turnover rates in cove forest canopies of about 1 to 2 percent per year, with 9.5 percent of the canopy in recent gaps (Runkle 1985).

These forests also experienced larger disturbances. For example, an 1840s recruitment peak in Joyce Kilmer, an old-growth cove forest in western North Carolina, coincides with historical accounts of a hurricane in 1835, and a second recruitment peak coincides with an ice storm in 1915 (Butler et al. 2014). Patterns of larger-scale natural disturbances in the southern Appalachians reflect the region's susceptibility to tropical storm remnants, wind and lightning storms, ice storms, debris avalanches and flood scour on steep creek valleys after intense rain storms, periodic and severe drought, and fire (White et al. 2011). Natural disturbances resulting in stand replacement occur once every several hundred years at most on individual sites (Butler et al. 2014; Pederson et al. 2014).

Although natural fires do occur in the southern Appalachians (Cohen et al. 2007), most fires in the last century have resulted from human ignitions. After suppression became effective in the 1940s, human-caused and lightning fires continued, but suppression reduced fire sizes and fire became much less frequent. The topographic and moisture gradients that control forest composition and structure also control fire behavior in the humid southern Appalachian landscape, and even in extreme conditions, fires leave behind a mosaic of unburned, low-severity, moderate-severity, and high-severity patches. Although mesic forests have a low incidence of fire, old-growth submesic to xeric stands were shaped by fires in the presuppression era. During the suppression era, species favored by fire, such as *Pinus rigida* and *Pinus pungens*, have declined. Fire, with wind and other disturbances, plays an important role in oak regeneration, as well (Lafon et al. 2017).

A second disturbance agent, and one that interacts with fire in xeric pine stands, is the southern pine beetle, a native insect. When older susceptible pines are aggregated, as they can be if regenerating in older burned patches, beetle outbreaks result in patches of fuel load that can increase the frequency and severity of fire. Without fire, southern pine beetle-caused mortality accelerates succession to hardwoods.

Beginning with chestnut blight in the 1920s, a series of nonnative, invasive pathogens and herbivores have influenced southern Appalachian forest types (Harmon et al. 1983; chapter 12). Chestnut canopy trees, eliminated by about 1950, were once among the largest and most dominant trees, particularly in submesic to subxeric forests. Recruitment peaks in old-growth cove stands in the Joyce Kilmer Memorial Forest between 1920 and 1940 may have been due to a combination of ice storms, severe drought, late spring freezes, and chestnut mortality (Butler et al. 2014). Balsam woolly adelgid began spreading through high elevation spruce-fir forests in 1956, causing widespread mortality to mature Fraser firs (*Abies fraser*; Kaylor et al. 2017). Hemlock woolly adelgid entered the southern Appalachians in the early-2000s and is causing the loss of a large and dominant tree of the old-growth forest remnants. Other invasive pests and diseases include beech bark disease, butternut canker, dogwood anthracnose (Jenkins et al. 2007), and the currently invading emerald ash borer. Other indirect human influences include the European wild boar; locally large deer populations; atmospheric pollutant deposition, including acid rain, nitrogen deposition, and near-ground ozone exposure (Sullivan 2017); and the projected effects of climate warming.

There is an ongoing conservation response to many of these threats, with regional efforts most focused on invasive species and pollutant deposition. For example, researchers are seeking to create blight-resistant chestnut trees, while chemical and biocontrol trials are underway for the hemlock woolly adelgid. Fraser fir reproduced prolifically in stands affected by the first wave of the balsam woolly adelgid invasion from 1960 through 1980. Consequently, there is a possibility that some of these stands will be able to contribute another regeneration cohort before the next infestation (Kaylor et al. 2017). In addition, conservation efforts are aimed at preventing the movement of the emerald ash borer by restricting the movement of firewood. Finally, because Great Smoky Mountain National Park is rated a Class I Airshed under the Clean Air Act, substantial research has been carried out on pollutant deposition and near-ground ozone exposure in the park to provide evidence in regulatory efforts to increase air quality (e.g., Fakhraei et al. 2016).

Structure of Old Growth in Great Smoky Mountains National Park in the 1930s and 1990s

The distribution and variability of old-growth forests of Great Smoky Mountains National Park (plate 3) reflect the natural and human disturbances we have reviewed above. In the park, forests not disturbed by logging or settlement occupy an estimated 21 percent of the park landscape (figure 4-1a). These forests are not a random sample of the original landscape but are biased towards higher elevations, with settlement and diffuse disturbances covering lower to middle elevations and logging covering most of the elevation gradient (figure 4-1b).

The National Park Service employed forest ecologist Frank Miller to carry out a vegetation survey in the 1930s, just as the park was completing land purchases. This dataset forms a unique quantitative view of the park, just after chestnut blight was entering the area (decades before other invasive pests) and just as fire suppression was becoming effective. We used this dataset in two ways, as described below, to illustrate the complexity of historic and ongoing disturbances in the southern Appalachian landscape.

To estimate the importance of indirect human disturbance across this landscape, we used species distribution models developed by Tuttle and based on the 1930s data for five dominant tree species (American chestnut, Fraser fir, hemlock, beech, and pitch pine). These models use plot occurrences to predict species frequency from an elevation and landform index (Tuttle unpublished; figure 4-2). The models indicate the potential impact of chestnut blight, balsam woolly adelgid, hemlock woolly adelgid, and beech bark disease, with the pitch pine model used as surrogate for the potential effects of fire suppression on the most xeric slope positions. These models show that the disturbances affect, with varying degrees, all parts of

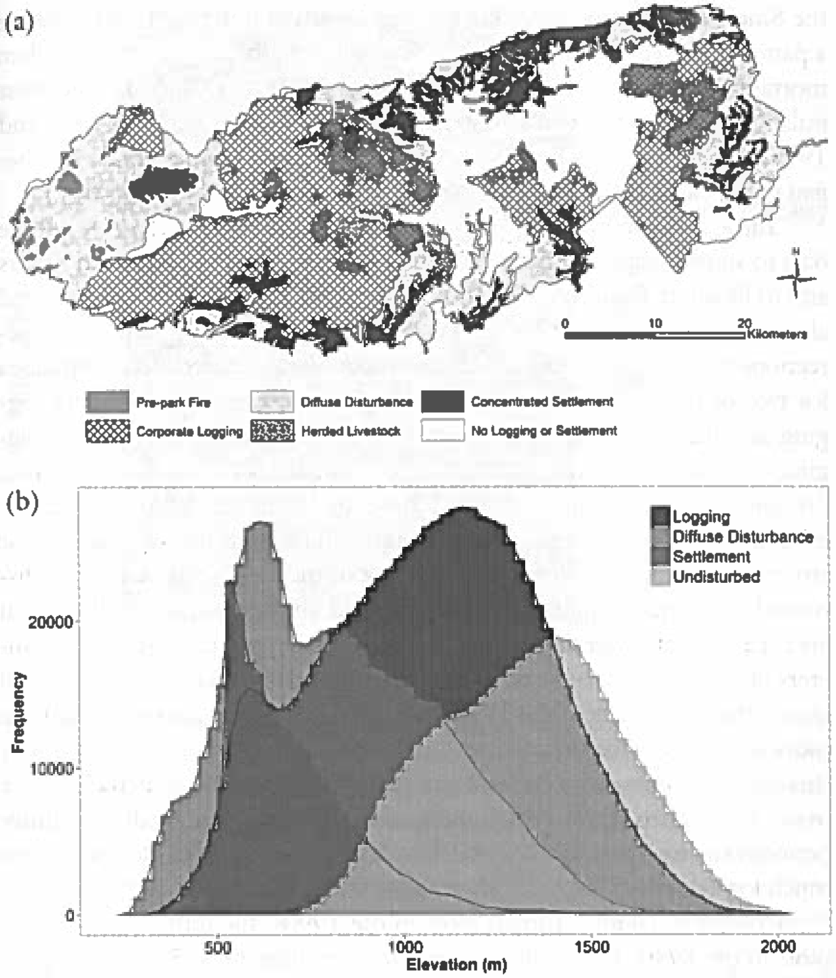

FIGURE 4-1. (a) Disturbance history of Great Smoky Mountains National Park (Pyle 1985, as modified by Tuttle). (b) Distribution of disturbance categories by elevation showing that remnant undisturbed forests are biased towards higher elevations. (The spike in settlement and diffuse disturbance at an elevation of about 550 meters shows the effect of Cades Cove, an unusual limestone window in the western part of the park that has relatively flat topography.)

the Smokies landscape. The disturbances began at different times, causing a pattern of overlap in time as well. Chestnut blight caused near complete mortality of canopy chestnut trees between 1930 and 1950. The heaviest pulse of mortality from balsam woolly adelgid occurred between 1975 and 1990. The invasions of hemlock woolly adelgid and beech bark disease began in the early-2000s and are ongoing in 2017.

Tuttle also compiled 1990s vegetation data for the park and used these data to show both the temporal and spatial variability of old-growth forests and to illustrate the effects of the natural and human disturbances reviewed above (Tuttle and White 2016). Pyle's (1985) disturbance map (with corrections by Tuttle) was used to classify plots. We have extracted summaries for two of Pyle's categories (figure 4-1a): "undisturbed" (no prepark logging or settlement) and "diffuse disturbance" (not subject to largescale logging or settlement but with diffuse direct human disturbance like grazing, fire, and selective cutting). After matching the 1930s and 1990s datasets for environmental conditions (see Tuttle and White 2016 for methods), clear structural differences emerge. The forests of the 1930s that were not disturbed by prepark logging or settlement had about 4 percent higher basal area, 15 percent lower density, and 14 percent higher quadratic mean diameters (a measure of average tree size that weights large trees more than small trees) than the forests of the 1990s (table 4-1). The data also show that the plots with diffuse disturbance changed between the 1930s and 1990s, but this comparison shows a different pattern: Basal area was 35 percent lower in the 1930s than in the 1990s, and quadratic mean diameter did not differ between the two periods. For the diffuse disturbance plots, densities were much lower in the 1930s, by 53 percent, than in the 1990s.

Compared to undisturbed plots in the 1990s, the diffuse disturbance plots in the 1990s had about 11 percent lower basal area, 5 percent higher density, and 10 percent lower quadratic mean diameter (table 4-1). Thus, the plots with diffuse disturbance show the legacy of the generally higher level of disturbance they sustained, compared to the undisturbed plots.

The increase in density in both disturbance categories over about 65 years has several probable causes: Fire suppression allowed ingrowth to stands with the most severe fire (e.g., those on xeric and subxeric sites, Harrod et al. 2000), and loss of American chestnut and Fraser fir due to forest pests resulted in increased sapling and small tree densities. Hemlock, one of the species that likely increased following loss of the chestnut, had not yet experienced decline when the 1990s data were collected. Thus, hemlock may have contributed to increased density in the 1990s plots, although it was undergoing largescale mortality in all size classes in 2017. Loss of dominant

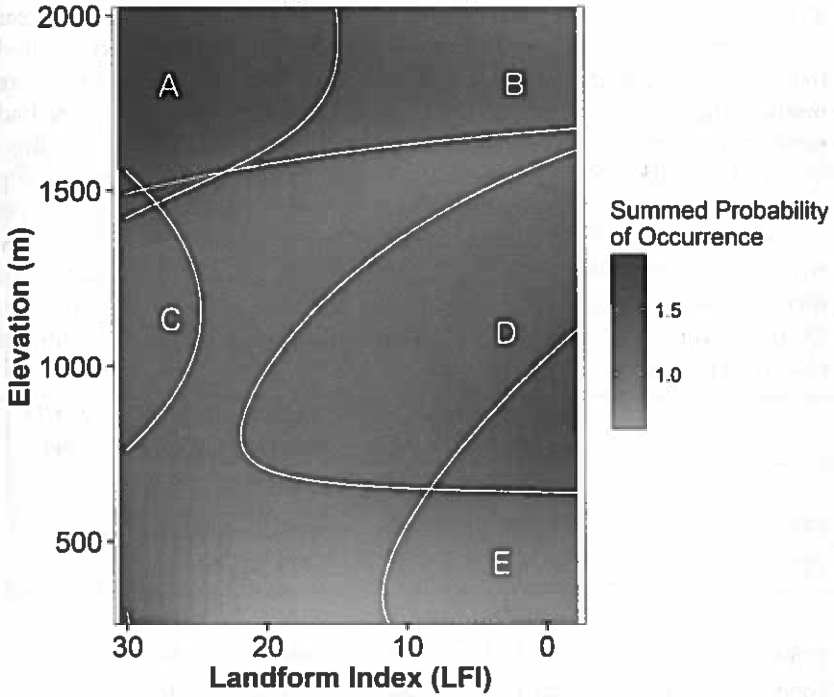

FIGURE 4-2. Distribution of five indirect human disturbances that cause mortality of large canopy trees in Great Smoky Mountains National Park as predicted from species distribution models for affected species based on elevation and landform index, an index developed for mountain landscapes that incorporates slope shape, slope position, and topographic shading (McNab 1993). A = *Fagus grandifolia* (a proxy for beech bark disease, which began in the 1990s), B = *Abies fraseri* (a proxy for balsam woolly adelgid, which began in the 1960s), C = *Tsuga canadensis* (a proxy for hemlock woolly adelgid, which began in the 2000s), D = *Castanea dentata* (a proxy for chestnut blight, which began in the 1930s), and E = *Pinus rigida* (a proxy for historic fire regime following suppression that began in the 1930s). The gray scale indicates the intensity of disturbance. (Overlapping intensities are summed, although the disturbances may not actually be overlapped on individual plots). White lines indicate the 50 percent probability levels for each of the disturbances. The models are constructed from species occurrence data from the 1930s data set described in the text. Other indirect human disturbances are not mapped, although they also affect large areas (e.g., pollutant deposition, which increases from low to high elevations, and near ground ozone exposure). See text for further discussion.

TABLE 4-1. The density and basal area of old-growth forests in Great Smoky Mountains National Park in the 1930s and 1990s (extracted from Tuttle and White 2016). Undisturbed plots are in forests that were neither logged nor subject to settlement; diffuse disturbance plots had some direct human impact, such as grazing, fire, and selective logging. The 1930s mark the beginnings of chestnut blight impacts and the fire suppression period. In the 1990s, hemlock woolly adelgid had not yet caused heavy mortality. The datasets have been matched so that they cover similar environments. See Tuttle and White (2016) for details of methods and analyses. BA = basal area, CV = coefficient of variation, QMD = quadratic mean stem diameter (a measure that is weighted towards larger trees).

	N	*BA* *m^2/ha*	*CV*	*Density* *Stems/ha*	*CV*	*QMD* *cm*
			Undisturbed plots			
1930s	132	39.3	.69	338.2	.98	40.1
1990s	167	37.8	.50	451.3	.66	34.5
			Diffuse disturbance plots			
1930s	250	21.2	.86	253.4	.51	31.5
1990s	188	32.4	.45	475.8	.46	31.3

American chestnut and Fraser fir trees likely also contributed to the decrease in basal area and quadratic mean diameter in undisturbed plots between the 1930s and 1990s. Although these same factors (fire suppression and loss of American chestnut and Fraser fir as dominant trees) likely contributed to the increase in density in diffuse disturbance plots, much lower 1930s basal area indicates the effects of prepark human disturbances in these plots, as well. Looking to the future, the ongoing mortality of hemlock and beech, and the continued response to earlier disturbances, means that changes in the structure in undisturbed plots will continue in this landscape.

A Framework for Old Growth in the Southern Appalachians

Given the history and ongoing natural and human disturbances in the southern Appalachians, what is the best framework for evaluating, delineating, and conserving old-growth forests? We answer this question by organizing old-growth criteria on three axes (figure 4-3; table 4-2). Two of these axes rep-

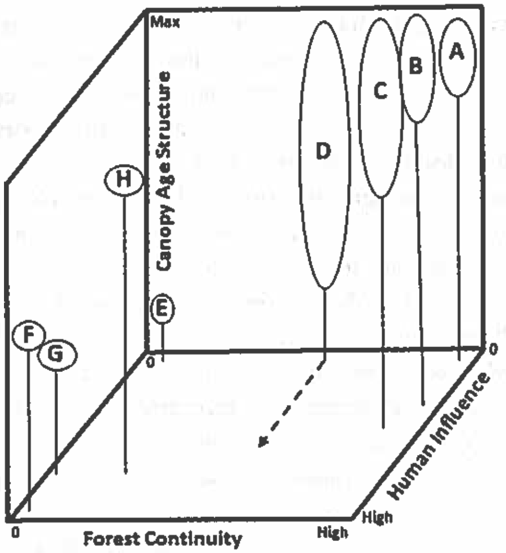

FIGURE 4-3. A three-dimensional framework for old-growth forests, incorporating canopy age structure, human influence, and forest continuity (see also table 4-2), with examples from Great Smoky Mountains National Park. Canopy age structure is an index relative to the maximum values expected for particular environments and the scale appropriate to natural disturbance and regeneration patterns. (Note that "age structure" is used rather than maximum tree age for the vertical axis because forest canopies usually contain a mix of tree ages; table 4-2.) Forest continuity is measured by the numbers of generations of trees during which the site has been a forest without direct, land-clearing disturbances by humans. Human influence ranges from none to direct, intentional, land clearing (logging and settlement), with nonland-clearing disturbances (invasive pests, fire regime change, atmospheric exposure to pollutants, and climate change) between these extremes. Together, canopy age structure and forest continuity produce late successional characteristics such as patterns of coarse woody debris and standing snags. The vertical length of the ovals represents variation in age structure at the landscape scale. Examples are from Great Smoky Mountains National Park: A. cove forest on sites originally without chestnut or hemlock and dominated by small scale gap dynamics; B. cove forests on sites originally with chestnut and/or hemlock as dominants; C. spruce-fir forests affected by the balsam woolly adelgid (forests with lower diversity and, thus, occupying more space on the vertical axis than cove forests); D. xeric pine-oak forests with stand-initiating natural fire regimes (the dashed line shows displacement for human set fires); E. debris-avalanche sites with open bedrock and primary succession; F. forests clear-cut during unregulated phase of mechanized logging pre-1930; G. abandoned farmed sites, settlement era; H. abandoned Native American fields. Note that ovals for logged and farmed stands are smaller because recovery began in a narrow window of time when the park was established. The large gap between forests of higher (A–D) and lower continuity (F–H) is due to the exclusion of logging and settlement after 1934 in Great Smoky Mountains National Park.

resent the most frequently used old-growth criteria: age structure of the tree canopy and "naturalness," that is, lack of disturbance by humans. We add a third axis: old growth defined by forest continuity through time (Norden et al. 2014), regardless of the current age structure of the tree canopy. In a report on old growth in Great Smoky Mountains National Park, Johnson (1995) used the phrase "ecosystem age" to represent this concept. Forests with long continuity, through multiple generations of trees without direct human disturbance, have also been called "primary forest" (Ervin 2016; chapter 7). The three axes are seemingly self-evident descriptors of old-growth forest, yet they are not always simultaneously true of a particular forest and all of them present problems even when considered individually (table 4-2; Leverett 1996). It is not surprising, then, that papers often recommend flexibility in applying old-growth criteria (e.g., Region 8 Old-Growth Planning Team 1997). After discussing these three criteria (figure 4-3; table 4-2), we add a fourth dimension at the landscape scale.

Many old-growth characteristics result from the interaction of these axes. For instance, mixed age structures, the presence of standing snags, and large logs and coarse woody debris in all stages of decay are the result not only of the agedness of the canopy (axis 1), but also the number of previous generations of trees (axis 3). Late successional composition and structure are the result of multiple generations of forest trees (axis 3) but imply both aged trees (axis 1) and low human influence (axis 2). Tree age criteria (axis 1) are often set to a value that dates tracts to presettlement, preindustrial, or prelogging times, thus also identifying forests with moderate to long continuity as forest ecosystems (axis 3). However, some forests that originated on Native American old fields would qualify based on tree age alone (axis 1), even though they had direct human disturbance (axis 2). In the late 1990s, for instance, the age criterion in the southern Appalachians is often set to greater than or equal to 150 years for trees, but this criterion depends on species composition and is sometimes set as low as 80 years for some forest types (Region 8 Old-Growth Planning Team 1997).

Figure 4-3 suggests two alternatives for designating old-growth forests in our landscape: a narrow definition and an inclusive definition. Under the narrow definition, in which all three axes are at maximum values, no area of old growth remains in the southern Appalachians today because 1) indirect, diffuse human disturbances like forests pests and climate change mean that no areas are pristine (axis 2), and 2) natural disturbances result in stands that lack old trees (axis 1). The narrow view is not tenable as the basis of policy and would cause land managers to overlook the value of primary forests with long continuity as forests. Including continuity (axis 3) as a factor emphasizes the value of

TABLE 4-2. Criteria for old growth forest (expanded from Leverett 1996; see also Pyle 1985; Yost et al. 1994; Johnson 1995). The criteria are organized by three axes (see also figure 4-3). Axis 2 (human influence) and axis 3 (forest continuity) are sometimes implicitly combined when old growth is referred to as virgin, primeval, original, primary, ancient, or presettlement forest.

Canopy age structure (axis 1)

Tree-age criteria: Tree age relative to maximum longevity

In all-aged forests, only a percentage of trees are near maximum age, leading to: >majority of canopy at least ½ maximum age; median age > ½ maximum lifespan (Cogbill 1996); mean age >150 years (Cogbill 1996); oldest trees >200 years (Runkle 1996); trees old enough for owl nesting sites, 524 years (Norden et al. 2014); >150 years of age or older than settlement; older than rotational age for a managed stand (Tyrell 1996).

Tree-size criteria: Tree size relative to maximum size on a given site type

In all-aged forests, only a percentage of trees are near maximum size, leading to such criteria as: large trees over 75 centimeters DBH, >7 per hectare (Runkle 1996).

Challenges with age and size

Trees can be difficult to age because of rotting or hollow cores; maximum tree age and size vary along gradients and trees on unfavorable sites might not be large; density and size and age structure varies with scale (Busing and White 1993); trees near maximum size and life spans occur on long-abandoned Native American fields; old and large trees were left by loggers if they were noncommercial species or had poor form.

Successional status (axes 1, 2, and 3; also referred to as "climax" structure/composition)

Successional criteria: Composition

Steady state composition and structure; late successional composition; understory plants with long generation time, low reproductive allocation, limited dispersal (Norden et al. 2014); presence of preferred timber species (Paulson et al. 2016).

Successional criteria: Structure

Shade-tolerant canopy and reproduction, all-aged or uneven-aged structure; low light level at herb layer, 0.3–2 percent of light (Greenberg et al. 1997); trees with evidence of competition in shady environments (no large lower branches or branch scars, undivided trunks that only branch in or just below the canopy); pit-and-mound topography; soil with thick organic layer and macropores (Greenberg et al. 1997); large snags and coarse woody debris, logs in all stages of decay (e.g., >10 snags per hectare at least 10 centimeters DBH; Runkle 1996), >19 logs per hectare at least 30 centimeters DBH (Runkle 1996); 12 +6 decadent trees per hectare (Greenberg et al. 1997); tree crowns rounded or flattened; emergent tree crowns damaged by wind and lightning.

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TABLE 4-2. *continued*

Successional status (axes 1, 2, and 3; also referred to as "climax" structure/composition)
Successional criteria: Dynamics
Continuous reproduction; uneven aged; no net growth, equilibrial, mature or over-mature; gaps or turnover rate 0.6–2 percent per year (Runkle 1996); tree rings show several long growth suppression periods (Di Filippo et al. 2017).
Challenges with successional criteria
Large trees create large gaps, so light-demanding successional species can be retained in old growth; forest structure exhibits scale dependence and this varies by species and disturbance type (Busing and White 1993); natural disturbances can reset communities to earlier successional states; coarse woody debris is removed by some natural disturbances (flood scour) and redistributed to floodplains downstream; disturbance regimes vary with site, community, and time (e.g., climate variation); on extreme sites, such as thin-soiled, steep, talus slopes, early successional trees can reach old ages and be in stable populations.
Human influence (axis 2), (naturalness/pristineness)
Human-influence criteria
No or minimal human impact; affected only by natural conditions; forests never logged or farmed; developed only after natural disturbances (Bradshaw et al. 2015).
Challenges with human-influence criteria
Historical data may be inaccurate or absent; diffuse indirect human disturbances are universal; fire is hard to attribute to human or natural influence.
Continuity (axis 3)
Continuity criteria
Primary forest never logged regardless of current tree age, >1,000 years as continuous forest (Bradshaw et al. 2015); ancient woodland defined as sites with trees since 1600, 1700, or 1775 AD (Peterken 1996), regardless of human use; stand age >time since settlement.
Challenges of continuity criteria
Forest history is often hard to document for specific sites; highly selective logging may be difficult to map on the landscape; some chestnut trees were felled to reduce the risk of fire-initiating lightning strikes, with logs left in place, but this can be confused with selective logging; forests are hard to document prior to 1500–1800, depending on location (Norden et al. 2014).

forests that were never directly disturbed by logging or agriculture, even if they have—and will continue to have—natural disturbances and diffuse human impacts that prevent trees from attaining old age. Areas with little disturbance and high continuity, as well as old trees, can be mapped to represent the narrow definition of "old growth"—"old growth" in the more traditional sense.

Continuity has been emphasized as an important descriptor for old growth, particularly in Europe (Norden et al. 2014). Recently, Veldman et al. (2015) applied the concept to "grassy biomes," including woodlands, savannas, and grasslands, in Africa. They pointed to the role of grazing animals and fire, along with the difficulty of applying Clementsian successional concepts to define late-successional or climax status, as leading to a lack of recognition, appreciation, and conservation of old habitats that did not necessarily have old trees yet were old and continuous belowground. In this book, Peet et al. (chapter 3) convincingly characterize fire-maintained pine savannas of the southeast US as meriting old-growth status. These examples question the narrow approach of restricting old growth to self-reproducing, mixed-aged forests with late successional composition and structure. Continuity gives us the opportunity to place older tree canopies in the context of their successional development, thus incorporating the heterogeneity and absence of direct human impact that can be important for biodiversity (Flensted et al. 2016).

We propose adding a fourth set of criteria for assessing potential old-growth value: temporal and spatial scale. Although even isolated old trees have ecological value (Lindenmayer 2016), the successional dynamics of old-growth forests suggest that area and spatial context are critical to old growth function and resilience. Pickett and Thompson (1978) introduced the concept of "minimum dynamic area" for an ecosystem, defined as the area required to encompass patches of all successional ages, which are thus large enough to support ecosystem regeneration based on the pattern of natural disturbances (see chapter 8). As natural disturbances range from smallscale gap dynamics to largerscale disturbances in old-growth forests, the minimum dynamic area would need to be, following Shugart's (1984) estimates, a minimum of 50 times the scale of these patches. Larger-scale heterogeneity is needed to incorporate the biodiversity in all phases of disturbance and succession across the range of patch types and sizes.

Temporal scales must also be considered to capture functional values of old-growth forests. Turner et al. (1993) used two axes to graphically model dynamic stability: the ratio of disturbed area to landscape area, the concept behind Shugart's 50-to-1 rule, and the ratio of disturbance interval to recovery time, which represents the capacity of the system to recover between disturbances. As the continuity axis of old growth implies variation in the frequency and size of natural disturbance patches, the density and population structure of tree species would be expected to reflect species' responses to the historical range of variation of natural disturbance (Keane et al. 2009). In southern Appalachian mesic cove forests, Busing and White (1993) found that the coefficient of variation for population structure was scale dependent and that more light-demanding species, like tulip tree, had higher coefficients of variation across scales than shade-tolerant species, suggesting that the density of these species was a function of the history and intensity of wind disturbance. The fourth dimension proposed here, then, which includes both spatial and temporal components, emphasizes crucial functional aspects of old-growth tracts that depend on their size and heterogeneity, in addition to their age, naturalness, and continuity.

Conclusion

Valuable old-growth forests remain in the southern Appalachians, but an inventory of these forests needs to be completed using a consistent, regionwide approach. This is particularly needed for national forest lands to ensure conservation of tracts beyond those currently protected. An inventory should be based on a careful review and centralized archiving of logging and settlement records (completed or underway in the work of Quentin Bass and others), followed by field evaluation, as long-recommended by Messick (pers. comm.). LiDAR is a valuable new tool that should be used to map forest structure across the landscape as an adjunct to further historical research and field evaluation (Ervin 2016). Adding the idea of forest continuity to more traditional evaluation criteria is especially important in helping to identify areas for protection. Forests with continuity but lacking dominance by old trees and/or lacking late-successional structural and compositional status, especially those on sites with small maximum tree sizes (e.g., xeric sites), have been termed *cryptic old growth* by White (1995). There may be substantial acreage of such forests, and completing an inventory is a high priority (Messick pers. comm.). Field work should also assess how soils in ecosystems with continuity differ in physical and biological properties from those with varying degrees of past logging and settlement (chapter 10). Finally, an assessment of biodiversity of forests of long continuity, whether or not they are presently characterized by old trees, is needed, including insects, fungi, and other taxa that characterize hollow trees, snags, decaying logs, and undisturbed soils (chapter 11).

Larger spatial scales that capture structural and temporal heterogeneity contribute to old-growth functions, such as resilience and retention of biodiversity. The focus should be not just on the big tree stands or the older-successional states, but the complete mosaic of successional states that is possible at larger spatial scales to create tracts of minimum dynamic area and landscape resilience (Shugart 1984; Turner et al. 1993). For this reason, efforts should be made to designate old-growth landscapes where the value of old growth is improved by including second-growth lands on logged sites that have a high potential for recovery as old growth. As we argue here for the oldest patches, we posit that earlier successional patches are also needed and cannot be duplicated by highly modified and intensely managed successional patches. We believe that we can not only complete the identification and conservation of current old growth but we can also build larger landscapes that can themselves become the old-growth forests of the future.

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Chapter 5

Topography and Vegetation Patterns in an Old-Growth Appalachian Forest: Lucy Braun, You Were Right!

Julia I. Chapman and Ryan W. McEwan

The biologically diverse Appalachian forests of eastern North America are an especially interesting and important example of the complex relationship between physiographic factors (e.g., elevation), disturbance processes, and long-term shifts in forest composition. Due to the widespread and often intense land-use practices of Euro-Americans, particularly circa 1880 to 1930, past human activity is an important component of the pattern and process we observe in forests of eastern North American today. Only a few small parcels of forest remain where dynamics have been driven mainly by nonanthropogenic phenomena, and these old-growth forests provide a crucial window to the past and an important baseline for the present and future. Understanding the historical and contemporary drivers of long-term dynamics has become an increasingly important goal in ecology as anthropogenically driven declines in biodiversity, including extinctions, and undesirable shifts in community composition threaten the performance of ecosystems as well as the benefits derived from them by humans (Pimm et al. 2014).

In the brilliant series of papers that preceded her defining book, *Deciduous Forests of Eastern North America* (1950), E. Lucy Braun assessed the relationship between topographic features (e.g., elevation, aspect) and the distributions and associations of various plant species to describe how forest communities assemble according to landscape features. In her manuscript, "An Ecological Transect of Black Mountain, Kentucky," Braun (1940) describes the forces that delineate species community patterns, noting (p. 239–240): "The individualistic concept suggested by Gleason (1926) might be applicable here, where communities with rather definite visible expression are the result of sorting un-