Forest Ecology and Management 546 (2023) 121350

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Perspectives: The wicked problem of defining and inventorying mature and old-growth forests

Andrew N. Gray [a,*], Kristen Pelz [b], Gregory D. Hayward [c], Tom Schuler [d], Wade Salverson [e], Marin Palmer [f], Christian Schumacher [g], Christopher W. Woodall [h]

[a] *USDA Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97333, USA*
[b] *USDA Forest Service, Rocky Mountain Research Station, Santa Fe, NM, USA*
[c] *USDA Forest Service, Headquarters, Ecosystem Management Coordination, Anchorage, AK, USA*
[d] *USDA Forest Service, Forest Ecosystem Management Research, Washington, DC, USA*
[e] *USDI Bureau of Land Management, Washington, DC, USA*
[f] *USDA Forest Service, Pacific Northwest Region, Portland, OR 97204, USA*
[g] *USDI Bureau of Land Management, Washington, D.C., USA*
[h] *USDA Forest Service, Northern Research Station, NH, USA*

ARTICLE INFO

Keywords:
Old growth forest
Mature forest
Inventory
Definitions
Forest structure

ABSTRACT

Mature and old-growth forests are valued for biodiversity, carbon sequestration, habitat, hydrologic function, aesthetics, and spirituality, as well as Tribal and Indigenous histories, cultures, and practices. Over the last 500 years, land use change and industrialization have resulted in global declines in the area of older forests (however defined). The goal of this study was to identify concepts and indicators to define mature and old-growth forests across the vegetation types of the United States in order to quantify their abundance and distribution. Defining old growth has been described as a "wicked problem" that involves values, science, and management; requires multiple disciplines; and can be expressed from many contradictory approaches.

The most common approach to defining mature and old-growth forests is to place them in a successional continuum of increases in tree size, biodiversity, habitat niches, and structural diversity with forest age. Time since severe disturbance, including human impact, is often a consideration, although humans have influenced the development of many forests for millennia. The successional framework is less useful in low-productivity or frequently-disturbed forests, or where current structural diversity under fire suppression may not reflect historic or desired future conditions. In order to classify forests into "old" and "not old", existing structure-based approaches apply minima of one or more structural or compositional criteria. Site productivity and/or plant association is an element of many definitions.

Once defined, estimating the area of mature and old-growth forest presents challenges. The only comprehensive, consistent field data of US forests is the Forest Inventory and Analysis (FIA) network of >140,000 forested plots. While the 0.067 ha sample area of FIA plots limits the number of structural metrics that might be useful and the plot density cannot capture fine-scale spatial heterogeneity, measurements enable a granular application of multiple structural and compositional criteria by vegetation type at broad spatial extents, and the ability to track change consistently over time. Spatial models integrate field and remotely-sensed data to predict the distribution of structural classes at finer spatial grain, but with substantial error in high-resolution estimates. There does not seem to be a readily-available method to map mature and old-growth stands across a landscape with a high degree of accuracy. Identifying mature and old growth forests in a stand management context will likely require additional measurements, adjustments to criteria at local scales, and incorporation of social and traditional knowledge within a consistent definition framework.

---

[*] Corresponding author.
E-mail address: andrew.gray@usda.gov (A.N. Gray).

https://doi.org/10.1016/j.foreco.2023.121350
Received 1 June 2023; Received in revised form 31 July 2023; Accepted 10 August 2023

1. Introduction

Mature and old-growth forests are valued by people for a variety of qualities, including aesthetics, spirituality, biodiversity, carbon sequestration, habitat, cultural practices, and hydrologic function (Franklin et al., 1981; Moore, 2007; Spies and Duncan 2009). Across much of our planet, land use change and industrialization have resulted in dramatic declines in the area of old forests (mature and old growth, collectively) and degradation of desired old forest characteristics due to human use, invasive species, and long-term consequences of fire suppression (Williams, 2008; Davis et al., 2017; Hagmann et al., 2021). Rapidly changing climate threatens to further erode the integrity of old forests as trees that established decades or centuries ago become maladapted to the climate of current sites or are killed by uncharacteristic disturbance, drought, or pest and pathogen outbreaks (van Mantgem et al., 2009; Coop et al., 2020; Hartmann et al., 2022).

In the United States, Executive Order 14072 (2022) from the President effectively directed the USDA Forest Service and USDI Bureau of Land Management to “define, identify, and complete an inventory of old-growth and mature forests on Federal lands, accounting for regional and ecological variations” in order to conserve and restore them. Developing clear definitions of old-growth forests has been a struggle (e.g., Helms, 2004; Wirth et al., 2009), and has been described as a “wicked problem” that involves values, science, and management; requires multiple disciplines; and can be conveyed using varied and contradictory approaches (Pesklevits et al., 2011). Varied perspectives include utilitarian, aesthetic, ecological process, wildlife habitat, spiritual/ethical, cultural, and biodiversity, which bring political, ecological, and value elements into definitions of mature and old-growth forests (Fig. 1).

At its most basic, old forests may be characterized by old trees and low levels of human influence (Barton, 2018). Many scientific studies of old-growth consist of characterizing attributes of forests selected as examples of old growth (e.g., Ruggiero et al., 1991; Fraver and Palik, 2012), not identifying what makes a particular forest old-growth and another not (e.g., Franklin et al., 1986). Specificity is necessary in order to apply definitions on the ground, which implies that some forest attributes will be more important, or at least better indicators, than others. However, for definitions to be useful, they must be readily applied without an inordinate amount of effort, so there is an unavoidable tension between specificity and practicality in any definition. Broadly useful definitions must also consider the substantial range of forest types; old-growth concepts have been primarily applied to specific moderate and high productivity, timber-producing forest types, and may not easily translate to dry or sparse forest types.

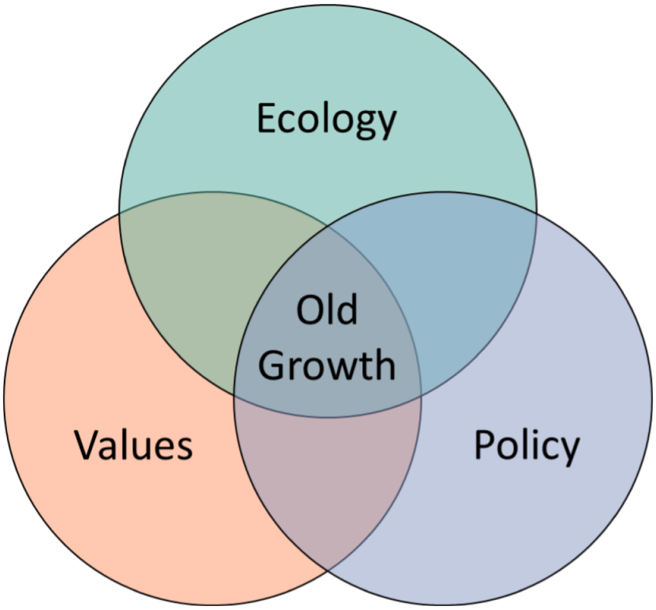

Fig. 1. Definitions of old-growth forests tend to lie at the intersection of considerations of ecology, policy, and values.

Controversies in the United States around management of older forests in the 1980 s focused on in the Pacific Northwest led the USDA Forest Service to adopt a generic definition of old growth as: “ecosystems distinguished by old trees and related structural attributes. Old-growth encompasses the later stages of stand development that typically differ from earlier stages in a variety of characteristics, which may include tree size, accumulations of large dead woody material, number of canopy layers, species composition, and ecosystem function” (USDA FS, 1989). In the early 1990 s, Forest Service regions across the country developed more specific criteria that varied by forest type and (often) forest productivity. In some regions these have been refined since then, and the current definitions have been used to create national estimates of the area of old-growth forest (Pelz et al., in review, this issue). The difficulty in settling on old-growth definitions has expanded to now include definitions for mature forest, generally understood to mean forests nearing but not yet in old-growth condition, or the stage of forest development prior to old growth.

The recent emphasis on mature forests in policy discussions regarding the conservation of old-growth forests may be related to reasons such as: 1) mature and old growth forests can be very similar in composition, structure, and function, for example as wildlife habitat (Ruggerio et al. 1991); 2) old-growth forest may be scarce in many regions, but maturing forests may be seen as potential old growth of the future; 3) various publics may not recognize a distinction between mature the old growth forests (Steel 2009); and 4) inclusion of forests with less complex structure or younger than traditionally considered ’old growth’ has been promulgated by advocacy groups to influence potential management actions.

The objective of this paper is to explore the “wicked problem” of classifying mature and old-growth forests by: 1) synthesizing key concepts for defining mature and old-growth forests, 2) exploring practical ways of classifying and quantifying them, 3) describing approaches to inventory and monitor them, and 4) identifying limitations and challenges. Our work is not intended to be an exhaustive catalog of definitions that have been used, but rather a review of alternative definitional concepts and their application to quantify old forests to inform management and policy on federal lands.

2. Mature and old-growth forest concepts

2.1. A. Human cultural, aesthetic, and spiritual values

A wide range of intrinsic values have been ascribed to old-growth forests, including: old age and the continuity of generations nourishing a future forest; tall trees that instill humility; complexity that prompts questions of how people fit into Earth’s cycles; tranquility where people find peace and contemplation; natural conditions that provide a measure of what can be lost or destroyed, and beauty from the combination of sight, sound, smell, and touch (Moore, 2007). Old forests embody historic legacies for specific places and a link to an earlier time (Higgs et al., 2014), a “symbolic refuge from an increasingly commercialized world“ (Lee 2009). They provide banks of knowledge for complex ecosystems and blueprints for natural forest processes; provide options for future generations, an important part of our natural heritage to pass on for their enjoyment; high biodiversity; they reflect well on our values and ethics to co-exist with our environment; a source of inspiration about the wonders and mysteries of nature; and they produce healthy feelings (Kramer, 1992).

For Native American cultures that developed with, and in many cases shaped, the mature and old-growth forests of the U.S., there is a strong connection between the health of the people and the environment (Yazzie, 2007). Old growth can be associated with a combination of grandfather trees with an understory of multicohort recruitment trees to replace the aging grandfathers. Far from being admired places that are separate from and unaffected by humans as examples of “untrammeled nature” valued by the dominant culture, Native Americans value places where they harvest medicinal plants, berries, game, or old trees and bark for ceremonial or practical use (Eisenberg, 2023). People who have a sense of ownership in an area will tend to it and improve the ecosystem services as a result (Andersson et al., 2007). The process of burning forest holds cultural value that complements the utilitarian value of tending the forest for resources (Colenbaugh and Hagan 2023).

To the extent that descriptions of cultural values mention specific attributes, they seem to align well with the ecological attributes of large trees, old age, canopy layers, open understories, diverse plants and animals, and patchiness of large and small trees. Many of the values appear to depend on more than visual appearance or other sensations, however, and are tied to learning that these forests are rare, old, and have a diversity of species and functions. In addition to general value of the existence of mature and old growth forest, for many people their strongest values are tied to specific places and their experiences there (Bott et al., 2003).

2.2. Maturity and production

Much of the literature for operational definitions of mature forest is rooted in forest production science compared to primarily ecological concepts for old growth (ecological approaches to maturity are covered below). Tree maturity can be described in terms of expected species longevity, maximum reproductive (seed) output, maximum size (diameter and height), growth rate, or morphological features (e.g., crown shape, bark roughness). Maturity is mentioned in the Forest Service Organic Administration Act of 1897, where only “dead, matured, or large growth” trees could be sold and harvested. This guidance was replaced in the National Forest Management Act of 1976 and its implementing regulations; the current approach limits timber harvests from a forest to the amount that can be removed “annually in perpetuity on a sustained yield basis” (36 CFR 219.11 d(6)). In silviculture, maturity is often described in terms of the amount of tree volume in a stand and the rate at which it accumulates. “Culmination of mean annual increment” (CMAI) identifies the age where merchantable timber volume divided by stand age reaches its maximum (Fig. 2). Harvesting a regulated forest at the age of CMAI maximizes the timber produced from a specific area on a sustained yield basis, referred to as the “biological rotation”. This is different from the “financial rotation” which is

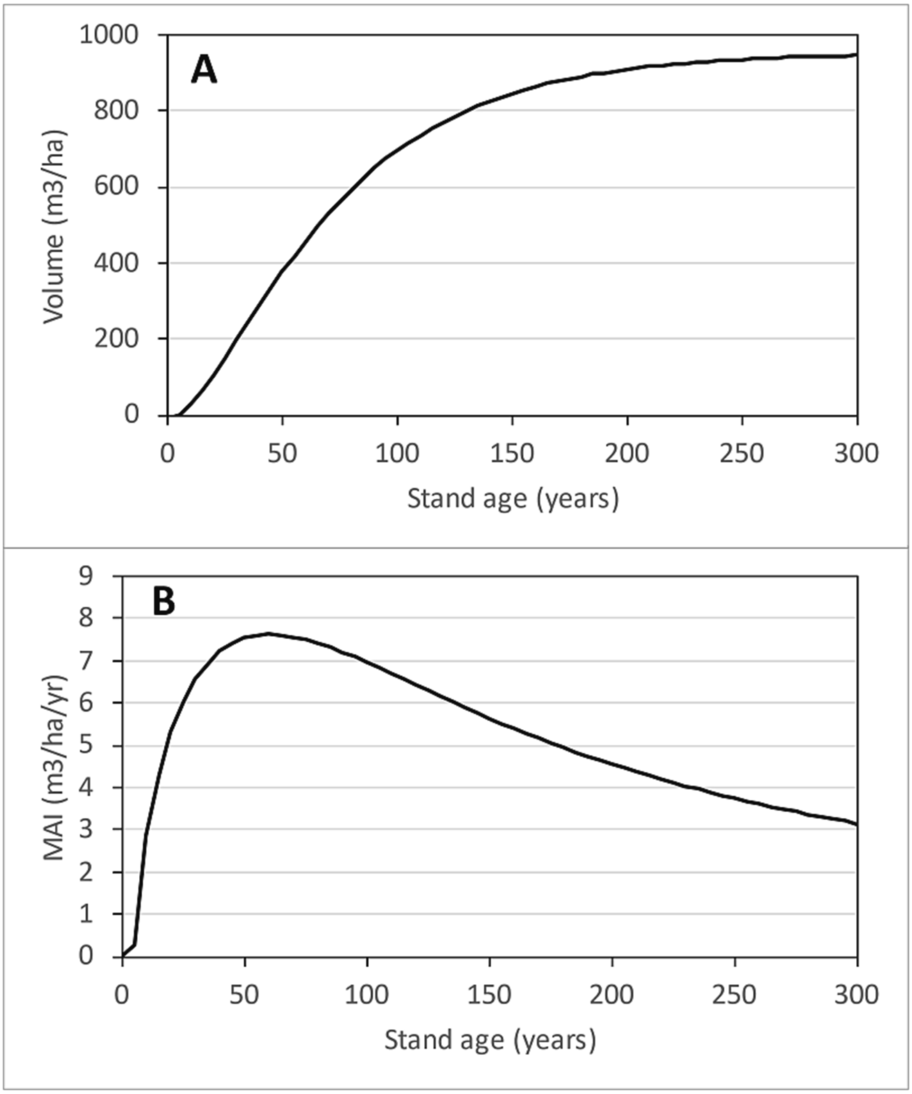

Fig. 2. Maturity is often expressed in terms of rates of forest volume accumulation. In this simplified example of predicted merchantable volume accumulation of forests of median site productivity and stockability in the western hemlock zone of the Pacific coast (Chisholm and Gray, in review), 90% of total volume accumulation occurs by age 160 (A), and culmination of mean annual increment occurs at age 60 (B).

determined by the net present value of revenue discounted by a chosen financial rate of return between harvests (Newman, 1988). Both concepts are generally related to stand-replacement harvest models rather than uneven-age management. For many professional foresters trained in the German tradition in the early and mid 1900 s, establishing a regulated forest required liquidating "decadent, unproductive" old-growth and replacing them with stands managed on a sustainable rotation (Langston, 1996). Many National Forest Plans describe the age of CMAI for different forest types as maturity and as target ages for regeneration harvest on appropriate land areas. Specifying CMAI for a particular forest stand usually entails use of growth and yield models; is affected by merchantability standards, site productivity, species composition, and intermediate harvest; and result in a broad range of ages at which CMAI occurs, as opposed to a sharp inflection point (e.g., Curtis and Marshall, 1993). Barnett et al. (2023) modeled forest carbon accumulation on stand age and defined the onset of old growth as the age of 95% of maximum carbon density, and the onset of mature as the peak average carbon increment.

2.3. Forest age

Advanced age is usually considered a prerequisite for mature and old-growth forests, and is usually the primary attribute researchers use to select stands for analysis (Ruggiero et al., 1991; Fraver and Palik, 2012). Whether a tree is old seems to have been judged based on human lifespans, but may also consider a species' typical longevity (Loehle, 1988). For example, 200 years is often considered old, regardless of whether the species typically lives for 350 years or 2,000. But species where individuals rarely survive past age 150, for example quaking aspen (*Populus tremuloides*) may be considered old-growth at age 100 (Mehl, 1992). In other cases, for example red alder (*Alnus rubra*), the species may be considered a seral stage succeeded by longer-lived species and not considered as potential old growth on its own (Davis et al., 2022). For a given forest type, old-growth attributes are often assumed to appear later on less productive sites than on more productive sites (e.g., Beardsley et al., 1999; Larson et al., 2008), but in some cases the reverse is true (Popp et al., 1992).

For many definitions, a minimum age is one of several criteria used to identify mature and old-growth forests. In one approach applied in Pacific Northwest forests, the mean of quantitative measures of structural attributes for stand ages 80 and 200 are used to identify mature and old-growth stands, respectively (Davis et al., 2022). Because the relationship between tree age and diameter, for example, is generally poor (Helms, 2004), tree size alone may not be a very useful indicator. For example, Van Pelt (2008) and Huckaby et al. (2003) found that old trees in dry, frequent-fire forests could be more reliably identified by morphological features of bark, branch size, and crown shape than by diameter.

Though age is clearly an essential aspect of defining 'older forests', obtaining accurate tree ages can be difficult or impossible: many tropical trees do not develop annual rings, large diameter trees or those with rot cannot be increment-cored to the pith, the years to attain coring height can vary markedly due to suppression of seedlings, hardwoods can be difficult to core, and missing annual rings are common, requiring cross-dating to obtain precise ages. While the age of a cohort that establishes after a severe disturbance, or the time since the disturbance, is often identified as stand age, the approach becomes difficult as the original cohort thins to a few individuals and other cohorts dominate the stand, creating a two-aged or multi-aged stand, sometimes referred to as an uneven-aged stand. Many forests develop from a series of small-scale (e.g., gap) or non-stand replacing disturbances. Consequently, they consist of trees with multiple ages or age cohorts, complicating the interpretation of an assigned "stand age" (Stevens et al., 2016). Despite the difficulties, tree and stand ages are useful concepts for understanding changes in stand structure and composition over time.

2.4. Structural development

Mature and old-growth forests are often identified as stages of forests that develop after severe disturbance. Oliver (1981) building on Bormann and Likens (1979) described a predictable sequence of four stages: stand initiation, where establishing or sprouting plants grow rapidly to fill newly-available growing space; stem exclusion, where new plants cannot establish due to lack of light and/or soil resources used by established plants; understory reinitiation, where the forest overstory "loses its grip" on the site and new or previously suppressed plants develop in the understory; followed by old growth, where the overstory canopy breaks up slowly as individual trees die, allowing understory trees to grow into the upper canopy. The old-growth processes continue in an uneven-age mosaic pattern of cohorts establishing in and around tree-mortality gaps until the next severe disturbance (Fig. 3). Franklin et al. (2002) proposed a more nuanced successional sequence that accounted for differences in the severity of the initial disturbance and the abundance of dead wood created, subsequently modified in Franklin et al. (2018). They identify a mature forest stage where the pioneer cohort of trees attains maximum height and crown spread, dead wood is at minimal levels, understory re-establishment occurs, causes of mortality shift from density-dependent to density-independent, and decadence develops in live overstory trees. The old forest stage is characterized by vertical diversification with multi-layered tree crowns, a high diversity of live and dead trees in a variety of sizes and conditions, abundant decadence in trees and downed wood, horizontal diversity composed of gaps, patchy regeneration, and dense tree clumps ("anti-gaps"). Instead of focusing on age and structure, an alternative approach is based on how the demographic processes, including the type and amounts of tree regeneration and mortality, change during stand development (Hayward, 1991).

Successional or forest development stages imply a linear sequence of development within distinct stand-level boundaries. However, frequent low-severity or infrequent moderate-severity disturbances, including fire, wind, insects, and disease, can move stands into different successional and structural classes, without reverting to the stand initiation stage (Aplet et al., 1988; Spies et al., 2018a). Because succession and disturbance can occur at a variety of scales in different forest types, some authors suggest avoiding artificial constraints on uniformity and area imposed by the stand concept and acknowledging old tree and old forest structure at the patch, stand, or landscape scales (Kaufmann et al., 2007; Pesklevits et al., 2011; Larson and Churchill, 2012). Frequent-fire ecosystems are discussed in more detail below.

Many definitions use forest structure to describe mature and old-growth forests because it is an easily measured substitute for organisms or processes that are difficult to measure (e.g., cavity-nesting nesting birds or plant growth) and because structure represents much of the aesthetic that humans respond to. A variety of measurable structural attributes may be useful, including live trees, large-diameter live trees, large-diameter branches, decadence in live trees, lower-canopy trees, ground vegetation, large dead trees, including snags and trees on the ground, tip-ups, organic layers, and their spatial patterns, including vertical distribution of crowns, horizontal distribution of structures, gaps and anti-gaps (Table 1) (Franklin et al., 2002). In addition to size, old trees differ from younger trees in many ways, including branch size and structure, proportion of heartwood, abundance of decay, and bark rugosity. The relative importance of different structures depends on vegetation type, productivity, disturbance history, and decay rates (Wirth et al., 2009). In most practical applications, minimum criteria are established for determining whether stands qualify as old-growth; for example, at least 20 trees per ha >81 cm in diameter. Other approaches develop indices of old-growthedness (Spies and Franklin 1988), for example, based on the density of large trees, which recognize gradients in forest structure and provide a measure of the quality or abundance of old-growth attributes in a stand (Kaufmann et al., 1992; Davis et al., 2022, Woodall et al., in review, this issue).

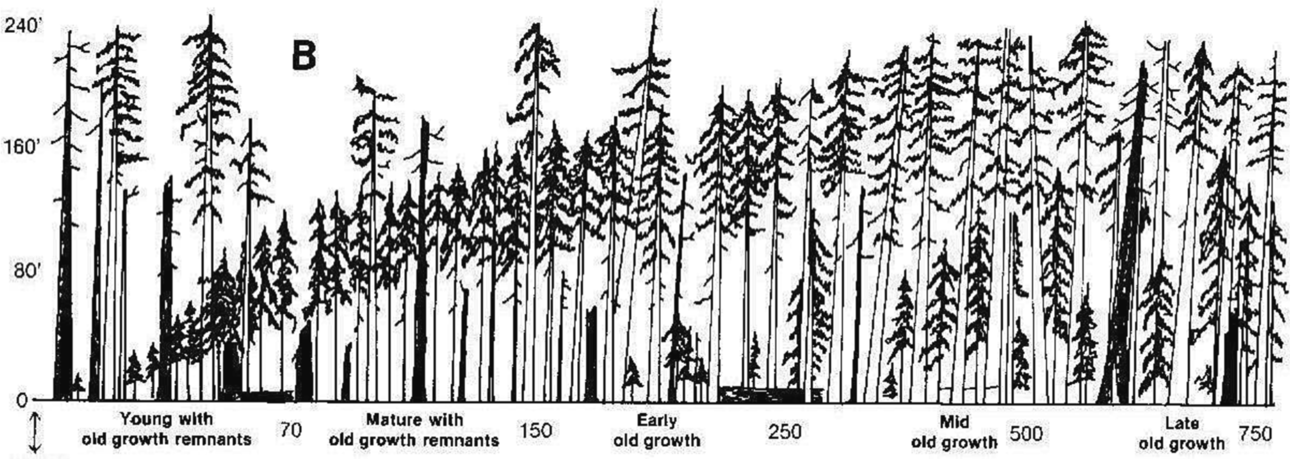

Fig. 3. Successional sequence of coastal Pacific Douglas-fir/western hemlock forest type following severe wildfire (from Franklin 1991).

Table 1
Structural features of forest stands used to quantify old growth attributes (from Franklin et al. 2002).

Structural features	Characteristics
Individual attributes	
Live trees	Species, density, mean diameter, range in diameter, height, canopy depth
Large-diameter live trees	Species, density, decadence and decay, crown condition, bark characteristics
Large-diameter branches	Species, density, size, arrangement, presence of arboreal "soil"
Lower-canopy tree community	Composition, density, height
Ground community	Composition, density, deciduous/evergreen
Standing dead trees (snags)	Species, size, decay state, density
Large woody debris (logs)	Species, size, decay state, volume, mass
Uproots (root wads and pits)	Density, size, age
Organic layers	Depth, chemical and physical properties, biota
Spatial patterns	
Vertical distribution of foliage/canopy	Depth, continuity, cumulative distribution
Horizontal distribution of structures	Spatial pattern (e.g., random, dispersed, or aggregated)
Gaps and anti-gaps	Size, shape, density

2.5. *Composition*

In a species succession context of stand development, the final stage occurs when all of the trees in the stand are "climax" species that established in the shade of other trees. In many forest regions, however, "pioneer" species that establish after severe disturbance can live for many centuries, and true climax forests are rare if they exist at all (e.g., Spies, 2004; Fraver and Palik, 2012). The Clementsian view of an ordered progression of species during stand development resulting in a stable, equilibrium climax community is not well-supported or expected to occur, due to disturbance. While disturbances like fire and clearcuts can promote pioneer species, hurricanes, avalanches, or insect outbreaks can promote release of climax species from the understory of the previous stand, so which species will dominate a site is not always predictable (Oliver, 1981; Wirth et al., 2009).

In some forest types tree species diversity tends to increase in older forests as shade-tolerant trees regenerate in the understory of established stands of pioneer species and grow into the canopy. While this tends to hold in more productive forest types, large or repeated fires, for example, can limit seed sources over large areas and the ability of shade-tolerant species to establish in mature stands where they would otherwise be expected (Gray and Franklin, 1997; Gray et al., 2009). In some forests however, establishment of shade-tolerant species in mature stages can end up precluding regeneration of other species. In less productive forest types with few species, or forests that experience frequent fire, there may be only one or two characteristic tree species that dominate all stages of development (Aplet et al., 1988; Youngblood et al., 2004; Sánchez Meador et al., 2010).

One of the primary values of old forests is as habitat for wildlife as well as biodiversity of many taxonomic groups, and provision of ecosystem functions (Wirth et al., 2009; Franklin et al. 2018). However, detecting and measuring populations of many organisms can be exceedingly difficult, and many species tend to key into specific habitat features rather than developmental stages. Ruggierio et al. (1991) is one of the only studies that examined how a wide range of fungi, plant and animal taxa varied among young, mature, and old-growth forests, and found numerous species that were more abundant in mature and old-growth than in natural young Douglas-fir (*Pseudotsuga menziesii*) forests. Even though some species are closely associated with old-growth forest, their presence or absence has not been used to define it (Loehle et al., 2015).

The loss of once-dominant species like American chestnut (*Castanea dentata*) and western white pine (*Pinus monticola*) to introduced pathogens and the ongoing impact of newly-introduced pathogens and insects like emerald ash borer (*Agrilus planipennis*) or balsam wooly adelgid (*Adelges piceae*) make it difficult if not impossible to recreate historical forest conditions (e.g., prior to European colonization). Dominance of understories by nonnative invasive plants may preclude successional development altogether without active management (Moser et al., 2009). Future mature and old-growth forests in plant communities significantly impacted by nonnative species will necessarily be a novel vegetation type.

2.6. *Human impact*

The international forest assessment framework developed by the United Nations Food and Agriculture Organization does not define old growth per se, but it does require countries to quantify the abundance of "primary forest" in regular reporting. Primary forest is defined as "naturally regenerated forest of native tree species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed" (FAO, 2018). Tree or forest age is not a criterion; a naturally-regenerating forest following wildfire or deglaciation could be primary forest. While the same requirement for lack of human impact has been suggested for old-growth forest (Barton, 2018), many definitions based on ecological attributes do not address it, and others mention the possibility that old growth could develop following human disturbance (USDA FS, 1989; Palik et al., 2002). In most regions of the U.S. where agriculture and logging have removed older forests, development of future mature and old-growth forests will only be possible from human-impacted ecosystems (Spies, 2004). In many scientific and policy assessments, human impact on forests is seen as a negative influence that degrades biodiversity and ecosystem function (e.g., Grantham et al., 2020). In many Native American belief systems, however, humans are embedded in nature, and extract resources and promote desired conditions with an eye to inter-generational sustainability (e.g., Eisenberg, 2023).

Native Americans significantly impacted the ecosystems they occupied by cultivating plants, harvesting plants and trees, hunting wildlife, and promoting conditions beneficial to a range of needs, often through the use of fire (Boyd, 1999; Yazzie, 2007; Abrams et al., 2022). Although it is known that many Native American cultures used fire for a variety of purposes (Roos et al., 2021; Colenbaugh and Hagan 2023), scientific consensus on the extent and details of their influence on fire regimes in many forests is lacking, even when "restoration" of fire to "frequent fire" forest types is a goal (e.g., Reynolds et al., 2013). Many dry, historically frequent-fire forest types in the U.S. are in danger of uncharacteristic high-severity fire due to more than a century of active fire suppression and indirect fire exclusion through intensive grazing. In many eastern forests, structure and composition of forests has changed with the cessation in broad-scale burning (e.g., Fralish et al., 1991).

In the western U.S., and on federal lands in particular, a substantial area of pre-settlement forest has been available for scientific study of disturbance history and stand development using dendrochronology and other means (e.g., Sánchez Meador et al., 2010; Merschel et al., 2014; Margolis et al. 2022). Although old growth forests are rarer in the eastern U.S., reconstructions in many ecosystems also indicate the importance of frequent fire in promoting forest structures found historically (e.g., Palik et al., 2002; Abrams et al., 2022; Colenbaugh and Hagan 2023).

In regions with very little area of old, unmanaged forests, promoting older forest structure and composition through ecological silviculture (i.e., active management that promotes restoration and sustainability of natural processes) has been proposed (D'Amato and Palik, 2021). In western ecosystems where fire was important historically, land managers, scientists, and policy-makers have advocated the use of partial harvest and prescribed fire to protect and promote mature and old growth forest (Reynolds et al., 2013; North et al., 2015; van Mantgem et al., 2016; Hessburg et al., 2021), although harvest of large fire-sensitive trees in some treatments has been criticized (e.g., Birdsey et al. 2023). Fire reintroduction is not risk free, however, and can result in greater initial mortality of old-growth trees than in unburned areas (e.g., Swezy and Agee, 1991).

2.7. Disturbance frequency

Forests that are frequently disturbed do not develop on the same trajectories as forests that experience infrequent stand-replacing disturbance. Low- or intermediate-severity disturbances that kill overstory trees (e.g., wind, insects, root disease) tend to accelerate stand development and recruitment of shade-tolerant species in gaps. In contrast, frequent low- or intermediate-severity fire tends to primarily kill understory trees and promote the survival of large, fire-resistant pioneer tree species. Old-growth structure in frequent-fire regime forests consisted of shifting mosaics of structural patches in all developmental stages that collectively constitute a stand that may be considered mature or old-growth (Fig. 4; Franklin et al., 2002; Spies et al., 2018b), or in a variety of patch sizes across a landscape (Kaufmann et al., 2007; North et al., 2009; Larson and Churchill, 2012). Abundance of shade-tolerant trees and layered canopies was low except in less fire-prone topographic positions, and levels of large snags and dead downed wood were much lower than in less frequent fire regimes (Lorimer and White, 2003; Fraver and Palik, 2012; Hessburg et al., 2015). Arraying different forest types in terms of typical (or desired) fire frequency and productivity may be a useful approach to identifying the importance of different structural attributes and processes in older forests (Fig. 5).

Climate change is affecting forests in large part by increasing the frequency and severity of fire, drought, storms, and insect outbreaks (Westerling et al., 2006; van Mantgem et al., 2013; Mueller et al., 2020). Development of mature and old-growth forest in the future will likely follow different trajectories when changes in climate alter disturbance regimes and species suitability (D'Amato and Palik, 2021).

3. Inventory and assessment methods

Once criteria have been developed to classify forested stands, patches, or landscapes into mature or old growth, quantifying their abundance and distribution requires multiple decisions on how to apply criteria to existing data, the accuracy and precision of the classification with alternative datasets, and the temporal and spatial scope of inference of the resulting estimates. Some of the advantages and limitations of alternative measurement approaches are presented below.

3.1. Targeted sampling

Most ecological and forestry studies use targeted sampling of specific vegetation types and conditions of interest. Many of the studies used to characterize mature and old-growth forests and describe their species composition and function identified stands meeting criteria for age, dominant species composition, and lack of recent disturbance or human manipulation (e.g., Runkle, 1981; Ruggiero et al., 1991; Palik et al.,

Fig. 4. Mosaic of patches characteristic of old growth in low- to moderate-intensity fire regimes (from Franklin et al. 2002; drawing by R. Van Pelt).

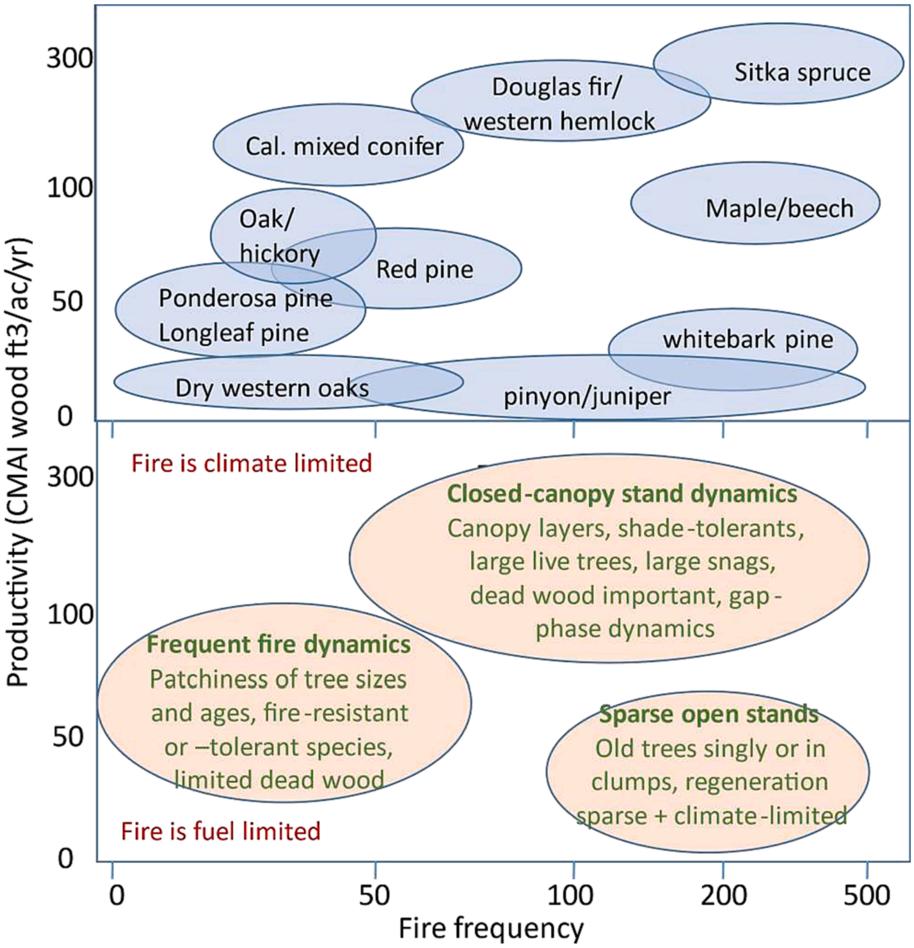

Fig. 5. Examples of US forest types arranged by fire frequency and productivity (top), and differences in process and structure expected (bottom).

1997). Long-term plots have been useful for understanding tree demography and the spatial patterns of tree mortality and regeneration in these forests (e.g., Acker et al., 1998; van Mantgem et al., 2009; Sánchez Meador et al., 2010). Areas measured within selected stands (i.e., plots) tend to be homogeneous with respect to plant community, disturbance history, and topography. Plots generally avoid stand edges and are often relatively large (≥1 ha) to be able to quantify tree population dynamics and spatial heterogeneity (e.g., Davies et al., 2021).

While targeted sampling has proved useful for describing the structure of mature and old-growth forests, the scope of inference of these measurements is difficult to define, and strictly would only apply to forests meeting the same criteria used to select the sample. It would be difficult to use targeted sampling to develop inventory estimates of the area of mature and old-growth forest without significant assumptions and substantial modeling. Targeted sampling may be the only way, however, to obtain data for vegetation types that are rare, or in regions where old-growth forests are rare (e.g., Tyrrell et al., 1998).

3.2. Strategic inventory

Strategic inventories are designed to estimate attributes over large areas, by sampling forests in a systematic fashion or employing other objective sampling designs. The national inventory in the U.S. has evolved since the 1930 s into the Forest Inventory and Analysis (FIA) program (Gillespie, 1999). The FIA design is based on a randomized-systematic grid of points across the nation, with measurements taken at points where land use that qualifies as forest intersects the plot footprint (Bechtold and Patterson, 2005). The base grid density is one point per 2,400 ha, with a sample area of 0.067 ha for trees >12.5 cm diameter at breast height (DBH), and 0.0054 ha for smaller trees. Individual live and dead trees are tracked over time with detailed measurements. Unbiased estimates of forest attributes (e.g., area by forest type, biomass by species) with known confidence intervals can be generated for regions and the nation, directly from the sample measurements. However, satellite imagery and other spatial layers are used through post-stratification to improve the precision of the estimates (Bechtold and Patterson, 2005). The confidence intervals vary depending on the attribute of interest, the number of plots in the domain of interest, and the variation captured by the post-stratification. For example, the area of National Forest reserved forestland in Washington state is estimated as 931 ± 40 thousand ha (total ± 95% confidence interval), while the area of US Fish & Wildlife forestland is estimated as 40 ± 16 thousand ha (Palmer et al., 2019).

Strategic inventories like FIA are designed to estimate means and totals of desired attributes for relatively large areas with an associated measure of uncertainty. Unlike targeted sampling, the full variation in forest composition and structure is measured in order to produce unbiased estimates. The measurements can also be used to classify forests, which is routinely done to describe forest type or tree density of individual FIA plots. However, the classifications are based on the plot sample, and may not accurately reflect the mean attributes of the overall stands in which they occur, which could cover 10 or more ha. In addition, the fixed plot footprint straddles stand and land-use boundaries, so the area sample for a stand may be substantially less than the full plot. Classifications that are based on plot measurements are affected by bias (one form of error) that decreases with increasing plot size and increasing density of the attribute being estimated (Azuma and Monleon, 2011). For example, a FIA-sized plot would not detect a large tree in a stand with 20 large trees per ha ~ 25% of the time, while a plot of twice the area would not detect a large tree in the same stand 5% of the time (Williams et al., 2001). Williams et al. (2001) recommend that classifications that depend on large areas or rare elements be avoided using inventory plots. The small size of the FIA plot and the dispersed subplot design also precludes the ability to characterize horizontal spatial heterogeneity (e.g., gaps and non-gaps).

Despite classification errors at the stand scale and the small plot size, applying consistent criteria to consistent measurements over time should provide users a realistic approximation of the relative change in abundance of forests meeting a mature or old-growth classification. Consistency should also enable comparisons of the relative abundance of forest meeting these criteria in different areas. The scope and quality of the FIA sample makes it indispensable for quantifying the current status of forest ecosystems, particularly at broad spatial extents. However, when using FIA plots to develop criteria, it is important to consider that currently- or recently-measured conditions may not reflect the historical, or potential, forest structure and composition that might be expected or desired for mature and old-growth forests (Spies et al., 2018a).

3.3. *Spatial models (maps)*

Spatial models (i.e., maps) of vegetation attributes have been created from a variety of remotely-sensed information, including aerial photography, satellite imagery, and lidar, and using a variety of interpretation or statistical techniques. From the 1950s until recently, vegetation maps used by managers were developed using photo-interpretation. Stereoscopic aerial photography provides high-resolution information on forest height and structure, but interpreters' delineation of landscapes into stands and vegetation classes is not always repeatable and the resulting maps tend to be inflexible to changing resource needs and questions.

Recent mapping efforts have modeled forest attributes from remote sensing, topographic, and climatic data tied to measurements from geolocated field plots. Maps can be created from statistical models of forest attributes (e.g., biomass), or imputation models that populate individual plots, or a mean of several plots, for every pixel across a landscape (Ohmann and Gregory, 2002, Wilson et al., 2013). While maps can provide estimates at fine scales (e.g., down to 30 × 30 m pixels for Landsat), estimates at small grain sizes (e.g., 10 ha) are not very accurate, even though agreement at broad scales is good (Kennedy et al., 2018). It is a common experience for modelers to encounter frustration from people who expect accurate classifications of individual stands, and end up not using the maps at all.

Fine-scale map predictions of older forests have been used to assess spatial pattern (e.g., patch size and connectivity), but map-based estimates are often summarized and presented at much broader scales (Davis et al., 2022). In productive forests that rapidly develop high levels of tree cover after disturbance, the Landsat signal tends to saturate with little change in spectral signatures as stands mature (Turner et al., 1999). Lidar data are more useful for differentiating forest structure than satellite imagery (e.g., Kane et al., 2019, Hudak et al., 2016), but their expense and the large amounts of data created have made acquisitions spatially and temporally inconsistent. The GEDI instrument has broad coverage in mid- and lower-latitudes but requires modeling with other datasets to provide spatial estimates between sample points (Dubayah et al., 2022).

One area of research involves developing models from a large pool of field plots outside of a focal area to inform estimates for relatively small areas with few plots, referred to as "small area estimation." These can improve the accuracy of estimates over that obtained from standard post-stratification of FIA plots (e.g., Mauro et al., 2017). Currently, however, there does not seem to be a readily-available method to delineate mature and old-growth forests across a landscape with a high degree of accuracy.

3.4. *Stand exams*

Some land managers have built spatial databases of their forest that track the history of measurements, treatments, and disturbances to individual stands. The data management requirements are substantial, however, and for public agencies in the U.S. that manage large areas, the availability of clean and consistent records (e.g., in Forest Service databases like FACTS and FSVEG) is uneven (but see Rehfeldt et al. 2015). Forest managers follow land management plans (LMPs) that identify goals and appropriate management actions for different zones in their area. These delineations are often based on detailed analyses of vegetation type, habitat for sensitive species, archeological sites, geomorphology, watershed conditions, and Congressional designations. While records and maps are likely available of past management treatments and general vegetation conditions, the ability to accurately classify the land base with a new definition for vegetation classes will be limited.

At the stand scale, standardized protocols have been developed to collect data from random points within a delineated area, called "stand exams." The protocols are well supported with agency software and databases, enabling detailed analyses of potential management actions for defined areas (e.g., https://www.fs.usda.gov/nrm/fsveg/). The effort to conduct stand exams is usually only done when specific stands have been identified for treatment, based on visual inspection, vegetation maps, or management records on past management history.

3.5. *Monitoring science and applications*

Future old forest monitoring efforts may be able to take advantage of alternative frameworks for definition and classification. Old forest monitoring has focused on construction of static, stand-level metrics linked to indicators of ecosystem processes (e.g., accumulation of dead wood and layered canopies) that enabled field-based classification of stages of stand development (e.g., Franklin et al. 1986, Kaufmann et al. 2007). These classifications can be applied to national inventories over time to estimate trends and identify proximate drivers of change in mature and old-growth forests. Contemporary data streams (e.g., annual inventories, remotely-sensed data) and refined modeling/inference approaches (e.g., Bayesian and machine learning) may afford novel and potentially more robust approaches to classifying mature and old-growth forests. First, rates of global change and associated effects on forest ecosystems (van Mantgem et al. 2009) may necessitate classification approaches that are equally dynamic in a manner similar to data-driven approaches to classifying forest types (Valle et al. 2014). The long-standing development patterns of site-specific forest types may rapidly change as species ranges shift resulting in novel systems. Second, approaches to classifying stages of stand development that use models of forest change such as culmination of mean annual increment (e.g., Barnett et al. 2023) may need to be dynamically calibrated and/or revised with contemporary data as climate change alters forest dynamics across space and time (Hagmann et al. 2021). Third, emerging paradigms in the forest sector such as greenhouse gas measurement, monitoring, reporting, and verification (MMRV) advances a paradigm that critical forest resource monitoring efforts should be objective and transparent to enable verification and associated management/policy development. Forest classification techniques might be expected to adhere to similar paradigms. Fourth, emerging approaches to statistical inference such as small area estimation techniques may offer more robust approaches to forest stand classification that can ingest a variety of data sources (strategic-scale forest inventories, Landsat change detection, local/regional LiDAR; Dubayah et al. 2022) across scales to fully inform the estimation of forest attributes. Finally, as classifying stages of stand development inherently incorporates social contexts (Wirth et al. 2009, Eisenberg 2023), the use of open-source code and data offers opportunities to engage the public beyond dialogues and at the interface of data analysis and reporting.

4. Conclusions

Solving the wicked problem of defining and quantifying mature and old-growth forests benefits requires the identification and selection of primary values and attributes, and compromises to select a limited number of characteristics that are meaningful and are practical to measure. Conceptual frameworks that consider how climatic and edaphic conditions, disturbance regimes, and species composition affect forest development can help ground a consistent approach across the rich diversity of vegetation types in the United States and elsewhere. The role of humans in promoting or restoring mature and old-growth forest is controversial, but fire history reconstructions and traditional ecological knowledge suggest that Native Americans had a significant impact on forest structure and function prior to Euro-American conquest, so their potential role in shaping mature and old forest could be considered alongside the role of ecological processes. Despite a wide range of developmental trajectories, even within a vegetation type, definitions require drawing sharp lines of "in" vs. "out," which necessitate some level of arbitrariness, whether it is picking thresholds of stand age or minimum density of trees greater than a certain diameter or some other, non-structural feature of these forests. Indices of "old-growthedness" based on stand characteristics can provide greater context and a sense of relative quality of old forest attributes among stands than a simple binary classification. Applying definitions to quantify the abundance of mature and old-growth forest is not an exact science either; field measurements provide site-specific precision but uncertainty at larger scales, while remote sensing techniques result in substantial uncertainty at local scales. Transparency about assumptions and the ability of different approaches to answer the implied scale and scope of different questions will aid future efforts to identify and quantify mature and old-growth forests.

CRediT authorship contribution statement

Andrew N. Gray: Conceptualization, Investigation, Writing – original draft. **Kristen Pelz:** Conceptualization, Writing – review & editing. **Gregory D. Hayward:** Conceptualization, Investigation, Writing – review & editing. **Tom Schuler:** Conceptualization, Investigation, Writing – review & editing. **Wade Salverson:** Conceptualization. **Marin Palmer:** Conceptualization, Writing – review & editing. **Christian Schumacher:** Conceptualization. **Christopher W. Woodall:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Andrew Gray reports financial support was provided by US Department of Agriculture Forest Service.

Data availability

No data was used for the research described in the article.

Acknowledgements

Comments from the public, resource professionals, and members of task teams contributed to the scope and content of this manuscript. Thanks to Ellis Margolis for thoughts and edits provided on an early draft, and thanks to Brian Palik, Jerry Franklin, and an anonymous reviewer for helpful comments on an earlier version of this manuscript.

References

Abrams, M.D., Nowacki, G.J., Hanberry, B.B., 2022. Oak forests and woodlands as Indigenous landscapes in the Eastern United States. J. Torrey Bot. Soc. 149, 101–121.

Acker, S.A., Sabin, T.E., Ganio, L.M., McKee, W.A., 1998. Development of old-growth structure and timber volume growth trends in maturing Douglas-fir stands. Forest. Ecol. Manag. 104 (1-3), 265–280.

Andersson, E., Barthel, S., Ahrné, K., 2007. Measuring social-ecological dynamics behind the generation of ecosystem services. Ecol. Appl. 17 (5), 1267–1278.

Aplet, G.H., Laven, R.D., Smith, F.W., 1988. Patterns of Community Dynamics in Colorado Engelmann Spruce-Subalpine Fir Forests. Ecology 69, 312–319.

Azuma, D., Monleon, V.J., 2011. Differences in forest area classification based on tree tally from variable- and fixed-radius plots. Can. J. For. Res. 41 (1), 211–214.

Barnett, K., Aplet, G.H., Belote, R.T., 2023. Classifying, inventorying, and mapping mature and old-growth forests in the United States. Frontiers in Forests and Global Change 5, 1070372.

Barton, A.M., 2018. Introduction: ecological and historical context. In: Barton, A.M., Keeton, W.S. (Eds.), Ecology and Recovery of Eastern Old-Growth Forests. Island Press, Washington DC, pp. 1–19.

Beardsley, D., Bolsinger, C., Warbington, R., 1999. Old-growth forests in the Sierra Nevada: by type in 1945 and 1993 and ownership in 1993. Res Pap PNW-RP-516. U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station , Portland, OR, 46 pp.

Bechtold, W.A., Patterson, P.L., 2005. The enhanced Forest Inventory and Analysis Program–national sampling design and estimation procedures. Gen Tech Rep SRS-80. USDA Forest Service, Southern Research Station, Asheville, NC, p. 85.

Birdsey, R.A., DellaSala, D.A., Walker, W.S., Gorelik, S.R., Rose, G., Ramírez, C.E., 2023. Assessing carbon stocks and accumulation potential of mature forests and larger trees in U.S. federal lands. Frontiers in Forests and Global. Change 5, 1074508.

Bormann, F.H., Likens, G.E. (Eds.), 1979. Pattern and Process in a Forested Ecosystem. Springer New York, New York, NY.

Bott, S., Cantrill, J.G., Myers Jr., O.E., 2003. Place and the Promise of Conservation Psychology. Hum. Ecol. Rev. 10, 100–112.

Boyd, R.T., 1999. Indians, fire, and the land in the Pacific Northwest. Oregon State University Press, Corvallis, OR.

Chisholm, P.J., Gray, A.N., n.d. *in review*. Forest carbon sequestration on the west coast, USA: role of species, productivity, and stockability. Plos One.

Colenbaugh, C., Hagan, D.L., 2023. After the Fire: Potential Impacts of Fire Exclusion Policies on Historical Cherokee Culture in the Southern Appalachian Mountains. Hum. Ecol. 51 (2), 291–301.

Coop, J.D., Parks, S.A., Stevens-Rumann, C.S., Crausbay, S.D., Higuera, P.E., Hurteau, M. D., Tepley, A., Whitman, E., Assal, T., Collins, B.M., Davis, K.T., Dobrowski, S., Falk, D.A., Fornwalt, P.J., Fulé, P.Z., Harvey, B.J., Kane, V.R., Littlefield, C.E., Margolis, E.Q., North, M., Parisien, M.-A., Prichard, S., Rodman, K.C., 2020. Wildfire-Driven Forest Conversion in Western North American Landscapes. Bioscience 70, 659–673.

Curtis, R.O., Marshall, D.D., 1993. Douglas-fir rotations–time for reappraisal? West. J. Appl. For. 8, 81–85.

D'Amato, A.W., Palik, B.J., 2021. Building on the last "new" thing: exploring the compatibility of ecological and adaptation silviculture. Can. J. For. Res. 51 (2), 172–180.

Davies, S.J., Abiem, I., Abu Salim, K., Aguilar, S., Allen, D., Alonso, A., Anderson-Teixeira, K., Andrade, A., Arellano, G., Ashton, P.S., Baker, P.J., Baker, M.E., Baltzer, J.L., Basset, Y., Bissiengou, P., Bohlman, S., Bourg, N.A., Brockelman, W.Y., Bunyavejchewin, S., Burslem, D.F.R.P., Cao, M., Cárdenas, D., Chang, L.-W., Chang-Yang, C.-H., Chao, K.-J., Chao, W.-C., Chapman, H., Chen, Y.-Y., Chisholm, R.A., Chu, C., Chuyong, G., Clay, K., Comita, L.S., Condit, R., Cordell, S., Dattaraja, H.S., de Oliveira, A.A., den Ouden, J., Detto, M., Dick, C., Du, X., Duque, Á., Ediriweera, S., Ellis, E.C., Obiang, N.L.E., Esufali, S., Ewango, C.E.N., Fernando, E.S., Filip, J., Fischer, G.A., Foster, R., Giambelluca, T., Giardina, C., Gilbert, G.S., Gonzalez-Akre, E., Gunatilleke, I.A.U.N., Gunatilleke, C.V.S., Hao, Z., Hau, B.C.H., He, F., Ni, H., Howe, R.W., Hubbell, S.P., Huth, A., Inman-Narahari, F., Itoh, A., Janík, D., Jansen, P.A., Jiang, M., Johnson, D.J., Jones, F.A., Kanzaki, M., Kenfack, D., Kiratiprayoon, S., Král, K., Krizel, L., Lao, S., Larson, A.J., Li, Y., Li, X., Litton, C.M., Liu, Y.u., Liu, S., Lum, S.K.Y., Luskin, M.S., Lutz, J.A., Luu, H.T., Ma, K., Makana, J.-R., Malhi, Y., Martin, A., McCarthy, C., McMahon, S.M., McShea, W.J., Memiaghe, H., Mi, X., Mitre, D., Mohamad, M., Monks, L., Muller-Landau, H.C., Musili, P.M., Myers, J.A., Nathalang, A., Ngo, K.M., Norden, N., Novotny, V., O'Brien, M.J., Orwig, D., Ostertag, R., Papathanassiou, K., Parker, G.G., Pérez, R., Perfecto, I., Phillips, R.P., Pongpattananurak, N., Pretzsch, H., Ren, H., Reynolds, G., Rodriguez, L.J., Russo, S.E., Sack, L., Sang, W., Shue, J., Singh, A., Song, G.-Z., Sukumar, R., Sun, I.-F., Suresh, H.S., Swenson, N.G., Tan, S., Thomas, S.C., Thomas, D., Thompson, J., Turner, B.L., Uowolo, A., Uriarte, M., Valencia, R., Vandermeer, J., Vicentini, A., Visser, M., Vrska, T., Wang, X., Wang, X., Weiblen, G. D., Whitfeld, T.J.S., Wolf, A., Wright, S.J., Xu, H., Yao, T.L., Yap, S.L., Ye, W., Yu, M., Zhang, M., Zhu, D., Zhu, L.i., Zimmerman, J.K., Zuleta, D., 2021. ForestGEO: Understanding forest diversity and dynamics through a global observatory network. Biol. Conserv. 253, 108907.

Davis, R.J., Gray, A.N., Kim, J.B., Cohen, W.B., 2017. Patterns of Change across the Forested Landscape. In: Olson, D.H., Horne, B.V. (Eds.), People, Forests, and Change: Lessons From the Pacific Northwest. Island Press, Washington D.C., pp. 91–101

Davis, R.J., Bell, D.M., Gregory, M.J., Yang, Z., Gray, A.N., Healey, S.P., Stratton, A.E., 2022. Northwest Forest Plan—The First 25 Years (1994–2017): Status and Trends of Late-successional and Old-growth Forests. Gen Tech Rep PNW-1004 U.S.

Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon, p. 82.

Dubayah, R., Armston, J., Healey, S.P., Bruening, J.M., Patterson, P.L., Kellner, J.R., Duncanson, L., Saarela, S., Ståhl, G., Yang, Z., Tang, H., Blair, J.B., Fatoyinbo, L., Goetz, S., Hancock, S., Hansen, M., Hofton, M., Hurtt, G., Luthcke, S., 2022. GEDI launches a new era of biomass inference from space. Environ. Res. Lett. 17 (9), 095001.

Eisenberg, C., 2023. Traditional ecological knowledge and active management of western forests. Western Forester 4–5.

Exec. Order No. 14072, 87 Fed. Reg. 24851 (April 22, 2022).

FAO, 2018. Global Forest Resource Assessment 2020: Terms and definitions. Food and Agriculture Organization of the United Nations, Rome, Italy, 32 pp.

Fralish, J.S., Crooks, F.B., Chambers, J.L., Harty, F.M., 1991. Comparison of Presettlement, Second-growth and Old-growth Forest on Six Site Types in the Illinois Shawnee Hills. Am. Midl. Nat. 125, 294–309.

Franklin, J.F., Cromack, K., Jr., Denison, W., Maser, C., Sedell, J., Swanson, F., Juday, G., 1981. Ecological characteristics of old-growth Douglas-fir forests. Gen Tech Rep PNW-118. USDA Forest Service Pacific Northwest Forest and Range Experiment Station, Portland, OR, 48 pp.

Franklin, J.F., Hall, F.C., Laudenslayer, W.F., Jr., Maser, C., Nunan, J., Poppino, J., Ralph, C.J., Spies, T.A., 1986. Interim definitions for old-growth Douglas-fir and mixed-conifer forests in the Pacific Northwest and California. Res Note PNW-447. USDA Forest Service Pacific Northwest Research Station, Portland, OR, 7 p.

Franklin, J.F., Spies, T.A., Pelt, R.V., Carey, A.B., Thornburgh, D.A., Berg, D.R., Lindenmayer, D.B., Harmon, M.E., Keeton, W.S., Shaw, D.C., Bible, K., Chen, J., 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest. Ecol. Manag. 155 (1-3), 399–423.

Franklin, J.F., Johnson, K.N., Johnson, D.L., 2018. Ecological Forest Management. Waveland Press, Long Grove, IL.

Fraver, S., Palik, B.J., Woods, K., 2012. Stand and cohort structures of old-growth Pinus resinosa-dominated forests of northern Minnesota, USA. J. Veg. Sci. 23 (2), 249–259.

U.S.D.A. Fs Old growth management; October 11 memo from Chief Robertson 1989 USDA Forest Service Washington DC 3 pp.

Gillespie, A.J.R., 1999. Rationale for a national annual forest inventory program. J. For. 97, 16–20.

Grantham, H.S., Duncan, A., Evans, T.D., Jones, K.R., Beyer, H.L., Schuster, R., Walston, J., Ray, J.C., Robinson, J.G., Callow, M., Clements, T., Costa, H.M., DeGemmis, A., Elsen, P.R., Ervin, J., Franco, P., Goldman, E., Goetz, S., Hansen, A., Hofsvang, E., Jantz, P., Jupiter, S., Kang, A., Langhammer, P., Laurance, W.F., Lieberman, S., Linkie, M., Malhi, Y., Maxwell, S., Mendez, M., Mittermeier, R., Murray, N.J., Possingham, H., Radachowsky, J., Saatchi, S., Samper, C., Silverman, J., Shapiro, A., Strassburg, B., Stevens, T., Stokes, E., Taylor, R., Tear, T., Tizard, R., Venter, O., Visconti, P., Wang, S., Watson, J.E.M., 2020. Anthropogenic modification of forests means only 40% of remaining forests have high ecosystem integrity. Nat. Commun. 11, 5978.

Gray, A.N., Monleon, V.J., Spies, T.A., 2009. Characteristics of remnant old-growth forests in the northern Coast Range of Oregon and comparison to surrounding landscapes. Gen Tech Rep PNW-790. Pacific Northwest Research Station, U.S. Department of Agriculture, Forest Service, Portland, Oregon, p. 45.

Gray, A.N., Franklin, J.F., 1997. Effects of multiple fires on the structure of southwestern Washington forests. Northwest Sci. 71, 174–185.

Hagmann, R.K., Hessburg, P.F., Prichard, S.J., Povak, N.A., Brown, P.M., Fulé, P.Z., Keane, R.E., Knapp, E.E., Lydersen, J.M., Metlen, K.L., Reilly, M.J., Sánchez Meador, A.J., Stephens, S.L., Stevens, J.T., Taylor, A.H., Yocom, L.L., Battaglia, M.A., Churchill, D.J., Daniels, L.D., Falk, D.A., Henson, P., Johnston, J.D., Krawchuk, M.A., Levine, C.R., Meigs, G.W., Merschel, A.G., North, M.P., Safford, H.D., Swetnam, T. W., Waltz, A.E.M., 2021. Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. Ecol. Appl. 31, e02431.

Hartmann, H., Bastos, A., Das, A.J., Esquivel-Muelbert, A., Hammond, W.M., Martínez-Vilalta, J., McDowell, N.G., Powers, J.S., Pugh, T.A.M., Ruthrof, K.X., Allen, C.D., 2022. Climate Change Risks to Global Forest Health: Emergence of Unexpected Events of Elevated Tree Mortality Worldwide. Annu. Rev. Plant Biol. 73 (1), 673–702.

Hayward, G.D., 1991. Using population biology to define old-growth forests. Wildl. Soc. Bull. 19, 111–116.

Helms, J.A., 2004. Old-growth: what is it? J. For. 102, 8–12.

Hessburg, P.F., Churchill, D.J., Larson, A.J., Haugo, R.D., Miller, C., Spies, T.A., North, M.P., Povak, N.A., Belote, R.T., Singleton, P.H., Gaines, W.L., Keane, R.E., Aplet, G.H., Stephens, S.L., Morgan, P., Bisson, P.A., Rieman, B.E., Salter, R.B., Reeves, G.H., 2015. Restoring fire-prone Inland Pacific landscapes: seven core principles. Landsc. Ecol. 30 (10), 1805–1835.

Hessburg, P.F., Charnley, S., Gray, A.N., Spies, T.A., Peterson, D.W., Flitcroft, R.L., Wendel, K.L., Halofsky, J.E., White, E.M., Marshall, J., 2021. Climate and wildfire adaptation of inland Northwest US forests. Front. Ecol. Environ. 20 (1), 40–48.

Higgs, E., Falk, D.A., Guerrini, A., Hall, M., Harris, J., Hobbs, R.J., Jackson, S.T., Rhemtulla, J.M., Throop, W., 2014. The changing role of history in restoration ecology. Front. Ecol. Environ. 12 (9), 499–506.

Huckaby, L.S., Kaufmann, M.R., Fornwalt, P.J., Stoker, J.M., Dennis, C. 2003. Identification and ecology of old ponderosa pine trees in the Colorado Front Range. Gen Tech Rep RMRS-110. US. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Hudak, A.T., Bright, B.C., Pokswinski, S.M., Loudermilk, E.L., O'Brien, J.J., Hornsby, B. S., Klauberg, C., Silva, C.A., 2016. Mapping Forest Structure and Composition from Low-Density LiDAR for Informed Forest, Fuel, and Fire Management at Eglin Air Force Base, Florida, USA. Can. J. Remote. Sens. 42 (5), 411–427.

Kane, V.R., Bartl-Geller, B.N., North, M.P., Kane, J.T., Lydersen, J.M., Jeronimo, S.M.A., Collins, B.M., Monika Moskal, L., 2019. First-entry wildfires can create opening and tree clump patterns characteristic of resilient forests. Forest. Ecol. Manag. 454, 117659.

Kaufmann, M.R., Binkley, D., Fulé, P.Z., Johnson, M., Stephens, S.L., Swetnam, T.W., 2007. Defining old growth for fire-adapted forests of the western United States. Ecol. Soc. 12, 15.

Kaufmann, M.R., Moir, W.H., Covington, W.W., 1992. Old-Growth Forests: What Do We Know About Their Ecology and Management in the Southwest and Rocky Mountain Regions? In: Kaufman, M.R., Moir, W.H., Bassett, R.L. (Eds.), Old-growth forests in the Southwest and Rocky Mountain Regions - Proceedings of a workshop. Gen Tech Rep RM-213. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 1-11.

Kennedy, R.E., Ohmann, J., Gregory, M., Roberts, H., Yang, Z., Bell, D.M., Kane, V., Hughes, M.J., Cohen, W.B., Powell, S., Neeti, N., Larrue, T., Hooper, S., Kane, J., Miller, D.L., Perkins, J., Braaten, J., Seidl, R., 2018. An empirical, integrated forest biomass monitoring system. Environ. Res. Lett. 13 (2), 025004.

Kramer, C.V., 1992. Ancient Forests- The Human Aspect. In: Kaufman, M.R., Moir, W.H., Bassett, R.L. (Eds.), Old-growth forests in the Southwest and Rocky Mountain Regions - Proceedings of a workshop. Gen Tech Rep RM-213. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 12-17.

Langston, N., 1996. Forest dreams, forest nightmares: the paradox of old growth in the inland West. University of Washington Press, Seattle, WA.

Larson, A.J., Churchill, D., 2012. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. Forest. Ecol. Manag. 267, 74–92.

Larson, A.J., Lutz, J.A., Gersonde, R.F., Franklin, J.F., Hietpas, F.F., 2008. Potential site productivity influences the rate of forest structural development. Ecol. Appl. 18 (4), 899–910.

Lee, R.G. 2009. Sacred Trees. In: Spies, T.A. and Duncan, S.L. eds., 2009. Old growth in a new world: a Pacific Northwest icon reexamined. Island Press, pp. 95-103.

Loehle, C., 1988. Tree life history strategies: the role of defenses. Can. J. For. Res. 18 (2), 209–222.

Loehle, C., Irwin, L., Manly, B.F.J., Merrill, A., 2015. Range-wide analysis of northern spotted owl nesting habitat relations. Forest. Ecol. Manag. 342, 8–20.

Lorimer, C.G., White, A.S., 2003. Scale and frequency of natural disturbances in the northeastern US: implications for early successional forest habitats and regional age distributions. Forest. Ecol. Manag. 185 (1-2), 41–64.

Margolis, E.Q., Guiterman, C.H., Chavardès, R.D., Coop, J.D., Copes-Gerbitz, K., Dawe, D.A., Falk, D.A., Johnston, J.D., Larson, E., Li, H., Marschall, J.M., Naficy, C. E., Naito, A.T., Parisien, M.-A., Parks, S.A., Portier, J., Poulos, H.M., Robertson, K.M., Speer, J.H., Stambaugh, M., Swetnam, T.W., Tepley, A.J., Thapa, I., Allen, C.D., Bergeron, Y., Daniels, L.D., Fulé, P.Z., Gervais, D., Girardin, M.P., Harley, G.L., Harvey, J.E., Hoffman, K.M., Huffman, J.M., Hurteau, M.D., Johnson, L.B., Lafon, C. W., Lopez, M.K., Maxwell, R.S., Meunier, J., North, M., Rother, M.T., Schmidt, M.R., Sherriff, R.L., Stachowiak, L.A., Taylor, A., Taylor, E.J., Trouet, V., Villarreal, M.L., Yocom, L.L., Arabas, K.B., Arizpe, A.H., Arseneault, D., Tarancón, A.A., Baisan, C., Bigio, E., Biondi, F., Cahalan, G.D., Caprio, A., Cerano-Paredes, J., Collins, B.M., Dey, D.C., Drobyshev, I., Farris, C., Fenwick, M.A., Flatley, W., Floyd, M.L., Gedalof, Ze'ev, Holz, A., Howard, L.F., Huffman, D.W., Iniguez, J., Kipfmueller, K.F., Kitchen, S.G., Lombardo, K., McKenzie, D., Merschel, A.G., Metlen, K.L., Minor, J., O'Connor, C.D., Platt, L., Platt, W.J., Saladyga, T., Stan, A.B., Stephens, S., Sutheimer, C., Touchan, R., Weisberg, P.J., 2022. The North American tree-ring fire-scar network. Ecosphere 13 (7).

Mauro, F., Monleon, V.J., Temesgen, H., Ford, K.R., Yang, J., 2017. Analysis of area level and unit level models for small area estimation in forest inventories assisted with LiDAR auxiliary information. PLoS One 12 (12), e0189401.

Mehl, M.H., 1992. Old-Growth Descriptions for the Major Forest Cover Types in the Rocky Mountain Region. In: Kaufman, M.R., Moir, W.H., Bassett, R.L. (Eds.), Old-growth forests in the Southwest and Rocky Mountain Regions - Proceedings of a workshop. Gen Tech Rep RM-213. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 106-120.

Merschel, A.G., Spies, T.A., Heyerdahl, E.K., 2014. Mixed-conifer forests of central Oregon: effects of logging and fire exclusion vary with environment. Ecol. Appl. 24 (7), 1670–1688.

Moore, K.D., 2007. In the Shadow of the Cedars: the Spiritual Values of Old-Growth Forests. Conserv. Biol. 21 (4), 1120–1123.

Moser, W.K., Barnard, E.L., Billings, R.F., Crocker, S.J., Dix, M.E., Gray, A.N., Ice, G.G., Kim, M.-S., Reid, R., Rodman, S.U., McWilliams, W.H., 2009. Impacts of Nonnative Invasive Species on US Forests and Recommendations for Policy and Management. J. For. 107, 320–327.

Mueller, S.E., Thode, A.E., Margolis, E.Q., Yocom, L.L., Young, J.D., Iniguez, J.M., 2020. Climate relationships with increasing wildfire in the southwestern US from 1984 to 2015. Forest. Ecol. Manag. 460, 117861.

Newman, D.H., 1988. The optimal forest rotation: a discussion and annotated bibliography. Gen Tech Rep SE-48. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC, p. 47.

North, M., Stine, P., O'Hara, K., Zielinski, W., Stephens, S., 2009. An ecosystem management strategy for Sierran mixed-conifer forests. Gen Tech Rep PSW-220. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.

North, M.P., Stephens, S.L., Collins, B.M., Agee, J.K., Aplet, G., Franklin, J.F., Fulé, P.Z., 2015. Reform forest fire management. Science 349 (6254), 1280–1281.

Ohmann, J.L., Gregory, M.J., 2002. Predictive mapping of forest composition and structure with direct gradient analysis and nearest neighbor imputation in coastal Oregon, USA. Can. J. For. Res. 32 (4), 725–741.

Oliver, C.D., 1981. Forest development in North America following major disturbances. For. Ecol. Manage. 3, 153–168.

Palik, B.J., Mitchell, R.J., Houseal, G., Pederson, N., 1997. Effects of canopy structure on resource availability and seedling responses in a longleaf pine ecosystem. Can. J. For. Res. 27 (9), 1458–1464.

Palik, B.J., Mitchell, R.J., Hiers, J.K., 2002. Modeling silviculture after natural disturbance to sustain biodiversity in the longleaf pine (Pinus palustris) ecosystem: balancing complexity and implementation. Forest. Ecol. Manag. 155 (1-3), 347–356.

Palmer, M., Kuegler, O., Christensen, G., Barker, J., Jovan, S., Mercer, K., Mills, J., Gray, A., Smith, R.J., Morgan, T., Marcille, K., 2019. Washington’s forest resources, 2007–2016: ten-year Forest Inventory and Analysis report. Gen Tech Rep PNW-976. USDA Forest Service, Pacific Northwest Research Station, Portland, OR, p. 79.

Pelz, K., Hayward, G., Gray, A.N., Berryman, E., Woodall, C., in review, this issue. An approach to quantify ‘old forests’ of the U.S. National Forest System using Forest Inventory and Analysis data. Forest Ecol Manag.

Pesklevits, A., Duinker, P.N., Bush, P.G., 2011. Old-growth Forests: Anatomy of a Wicked Problem. Forests 2, 343–356.

Popp, J.B., Jackson, P.D., Bassett, R.L., 1992. Old-Growth Concepts from Habitat Type Data in the Southwest. In: Kaufman, M.R., Moir, W.H., Bassett, R.L. (Eds.), Old-growth forests in the Southwest and Rocky Mountain Regions - Proceedings of a workshop. Gen Tech Rep RM-213. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 100-106.

Rehfeldt, G.E., Worrall, J.J., Marchetti, S.B., Crookston, N.L., 2015. Adapting forest management to climate change using bioclimate models with topographic drivers. Forestry: Int. J. Forest Res. 88 (5), 528–539.

Reynolds, R.T., Sanchez Meador, A.J., Youtz, J.A., Nicolet, T., Matonis, M.S., Jackson, P. L., DeLorenzo, D.G., Graves, A.D., 2013. Restoring composition and structure in Southwestern frequent-fire forests: A science-based framework for improving ecosystem resiliency. Gen Tech Rep RMRS-310. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, p. 76.

Roos, C.I., Swetnam, T.W., Ferguson, T.J., Liebmann, M.J., Loehman, R.A., Welch, J.R., Margolis, E.Q., Guiterman, C.H., Hockaday, W.C., Aiuvalasit, M.J., Battillo, J., Farella, J., and Kiahtipes, C.A. 2021. Native American Fire Management at an Ancient Wildland-Urban Interface in the Southwest US. Proceedings of the National Academy of Sciences, 118(4): e2018733118.

Ruggiero, L.F., Aubry, K.B., Carey, A.B., Huff, M.H., 1991. Wildlife and Vegetation of Unmanaged Douglas-fir Forests. Gen Tech Rep PNW-285. USDA Forest Service Pacific Northwest Research Station, Portland, OR, p. 533.

Runkle, J.R., 1981. Gap regeneration in some old-growth forests of the eastern United States. Ecology 62, 1041–1051.

Sánchez Meador, A.J., Parysow, P.F., Moore, M.M., 2010. Historical Stem-Mapped Permanent Plots Increase Precision of Reconstructed Reference Data in Ponderosa Pine Forests of Northern Arizona. Restor. Ecol. 18, 224–234.

Spies, T.A., 2004. Ecological Concepts and Diversity of Old-Growth Forests. J. For. 102, 14–20.

Spies, T.A., Duncan, S.L. eds. 2009. Old growth in a new world: a Pacific Northwest icon reexamined. Island Press.

Spies, T.A., Stine, P.A., Gravenmier, R., Long, J.W., Reilly, M.J., coords, t., 2018a. Volume 1—Synthesis of science to inform land management within the Northwest Forest Plan area. Gen Tech Rep PNW-966. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon, 370 pp.

Spies, T.A., Stine, P.A., Gravenmier, R., Long, J.W., Reilly, M.J., Mazza, R., coords, t., 2018b. Synthesis of science to inform land management within the Northwest Forest Plan area: executive summary. Gen Tech Rep PNW-970. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon, 186 pp.

Spies, T.A., Franklin, J.F., 1988. Old growth and forest dynamics in the Douglas-fir region of western Oregon and Washington. Nat. Areas J. 8, 190–201.

Steel, B.S. 2009. Common sense versus symbolism: the case for public involvement in the old-growth debate. In: Spies, T.A. and Duncan, S.L. eds., 2009. Old growth in a new world: a Pacific Northwest icon reexamined. Island Press, pp 116-126.

Stevens, J.T., Safford, H.D., North, M.P., Fried, J.S., Gray, A.N., Brown, P.M., Dolanc, C. R., Dobrowski, S.Z., Falk, D.A., Farris, C.A., Franklin, J.F., Fulé, P.Z., Hagmann, R.K., Knapp, E.E., Miller, J.D., Smith, D.F., Swetnam, T.W., Taylor, A.H., 2016. Average stand age from forest inventory plots does not describe historical fire regimes in ponderosa pine and mixed-conifer forests of western North America. Plos One 11, e0147688.

Swezy, D.M., Agee, J.K., 1991. Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. Can. J. For. Res. 21 (5), 626–634.

Turner, D.P., Cohen, W.B., Kennedy, R.E., Fassnacht, K.S., Briggs, J.M., 1999. Relationships between leaf area index and Landsat TM spectral vegetation indices across three temperate zone sites. Remote Sens. Environ. 70 (1), 52–68.

Tyrrell, L.E., Nowacki, G.J., Crow, T.R., Buckley, D.S., Nauertz, E.A., Niese, J.N., Rollinger, J.L., Zasada, J.C., 1998. Information About Old Growth for Selected Forest Type Groups in the Eastern United States. Gen Tech Rep PNW-197. USDA Forest Service North Central Research Station, St. Paul, MN, p. 505.

Valle, D., Baiser, B., Woodall, C.W., Chazdon, R., 2014. Decomposing biodiversity data using the Latent Dirichlet Allocation model, a probabilistic multivariate statistical method. Ecol. Lett. 17, 1591–1601.

van Mantgem, P.J., Stephenson, N.L., Byrne, J.C., Daniels, L.D., Franklin, J.F., Fulé, P.Z., Harmon, M.E., Larson, A.J., Smith, J.M., Taylor, A.H., Veblen, T.T., 2009. Widespread Increase of Tree Mortality Rates in the Western United States. Science 323 (5913), 521–524.

van Mantgem, P.J., Nesmith, J.C.B., Keifer, M., Knapp, E.E., Flint, A., Flint, L., Penuelas, J., 2013. Climatic stress increases forest fire severity across the western United States. Ecol. Lett. 16 (9), 1151–1156.

van Mantgem, P.J., Caprio, A.C., Stephenson, N.L., Das, A.J., 2016. Does Prescribed Fire Promote Resistance to Drought in Low Elevation Forests of the Sierra Nevada, California, USA? Fire Ecology 12 (1), 13–25.

van Pelt, R., 2008. Identifying Old Trees and Forests in Eastern Washington. In. Washington State Department of Natural Resources, Olympia, WA, 170 pp. https://www.dnr.wa.gov/publications/lm_hcp_eastside_oldgrowth_guide.pdf.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313 (5789), 940–943.

Williams, M., 2008. A New Look at Global Forest Histories of Land Clearing. Annu. Rev. Env. Resour. 33 (1), 345–367.

Williams, M.S., Schreuder, H.T., Czaplewski, R.L., 2001. Accuracy and efficiency of area classifications based on tree tally. Can. J. For. Res. 31 (3), 556–560.

Wilson, B.T., Woodall, C.W., Griffith, D.M., 2013. Imputing forest carbon stock estimates from inventory plots to a nationally continuous coverage. Carbon Balance Manag. 8, 1.

Wirth, C., Messier, C., Bergeron, Y., Frank, D., Fankhänel, A., 2009. Old-Growth Forest Definitions: a Pragmatic View. In: Wirth, C., Gleixner, G., Heimann, M. (Eds.), Old-Growth Forests: Function, Fate and Value. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp. 11–33.

Woodall, C.W., Kamoske, A., Hayward, G.D., Schuler, T., Hiemstra, C., Palmer, M., Gray, A.N., in review, this issue. Classifying Mature Federal Forests in the United States: The Forest Inventory Growth Stage System. Forest Ecol Manag.

Yazzie, V., 2007. The tribal perspective of old growth in frequent-fire forests—its history. Ecol. Soc. 12, 21.

Youngblood, A., Max, T., Coe, K., 2004. Stand structure in eastside old-growth ponderosa pine forests of Oregon and northern California. Forest. Ecol. Manag. 199 (2-3), 191–217.