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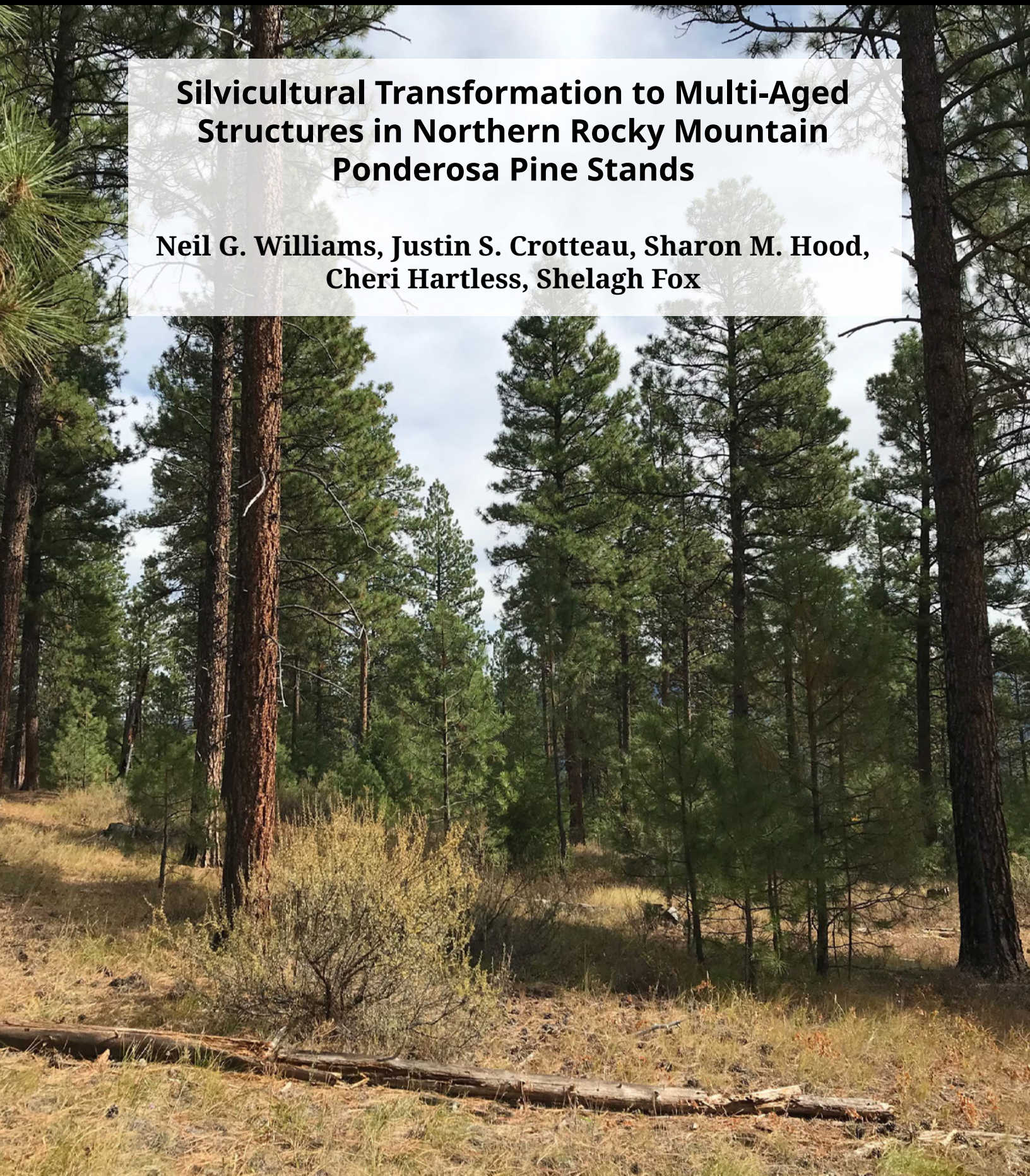
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Silvicultural Transformation to Multi-Aged Structures in Northern Rocky Mountain Ponderosa Pine Stands

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Abstract

Multi-aged stands dominated by ponderosa pine (*Pinus ponderosa*) once occupied large areas of the American west at low to mid elevations. Much of this forest type is now even-aged after regenerating from past high-severity disturbance (i.e., wildfire or even-aged harvesting) or is transitioning toward even-aged structure in the absence of natural disturbance processes. Although even-aged forests are well-suited to a subset of management objectives and sites, multi-aged forest structures are often better aligned with the multi-objective framework under which public forestland is commonly managed. Transformation silviculture is the pathway to shifting even-aged ponderosa pine stands to a wide range of potential multi-aged structures, but there are few practical resources to help managers overcome the real and perceived barriers to transformation. This practitioner-oriented guidebook was developed to help forest managers accomplish the transformation process in ponderosa pine stands. Our approach emphasizes flexibility, while providing hypothetical and real-world examples of transformation sequences, sustainable multi-aged structures, and silvicultural practices useful during transformation and in the subsequent long-term management of multi-aged stands. Although we use stands in the northern Rocky Mountain region as our study subject, much of the content is broadly applicable throughout ponderosa pine's range.

Keywords: Silvicultural transformation, multi-aged, uneven-aged, even-aged, ponderosa pine, management guide, stand structure

Cover: A multi-aged ponderosa pine stand on the Bitterroot National Forest in western Montana. USDA Forest Service photo by Neil Williams.

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Introduction



Figure I.1—These ponderosa pine exhibit the large bark plates and intense orange color that is characteristic of old trees. USDA Forest Service photo by Neil Williams.

This document is a guide to silvicultural transformation from even-aged to multi-aged structures in ponderosa pine (*Pinus ponderosa*) stands, with a focus on the northern Rocky Mountain region of the United States. In addition to transformation from simple, even-aged structures, we also discuss transformation in stands that have a ponderosa pine-dominated overstory, but are in the process of shifting toward, or away from, an even-aged structure because of infilling by more shade-tolerant species coupled with mortality of older overstory pines. In these latter cases, this infill typically homogenizes horizontal structure (also referred to as spatial pattern) and compromises long-term resource sustainability by reducing tree vigor and increasing disturbance and climate risks (Arno et al. 1995, 1997; Hagmann et al. 2021).

What Do We Mean by *Silvicultural Transformation*?

The *transformation* of a forest stand entails a shift from one age-class structure (e.g., an even-aged stand) to another (e.g., a two-aged stand) through a sequence of silvicultural treatments (O’Hara 2001, 2014; Pommerening 2006; Schütz, 2001, 2006). In the case of transformation from even-aged to multi-aged structure, this process involves regenerating and nurturing additional cohorts. Of course, natural stand dynamics and associated disturbance processes can also accomplish similar changes in age-class structure, a fact that is central to many models of stand dynamics on which silvicultural treatments are based (e.g., Oliver and Larson 1996). Transformation has also been referred to as *conversion* (von Lüpke et al. 2004; Manetti et al. 2020). However, for reasons articulated by O’Hara (2014), we favor the term *transformation*, which is independent of the changes in species composition that are sometimes also referred to as *conversion*.

The transformation from even-aged to multi-aged structure encompasses a huge envelope of possible age-class structures (box 1) and physical stand structures. Multi-aged stands—stands containing two or more cohorts of trees (O’Hara 2014)—include a wide range of age-class structures. Even within a single age class and forest type, vertical and horizontal structure may vary greatly, from stands that are structurally homogeneous to those that are extremely complex. Thus, both the starting point and the endpoint for the transformation we discuss represent an array of conditions. Further variability in the biophysical site characteristics, management objectives, and constraints on management freedom for any given stand create an almost limitless array of transformation contexts. To accommodate such diversity, in this guide we attempt to provide a flexible approach centered on examples and options, rather than prescriptive strategies or recommendations.

Why Implement Multi-Aged Management in Ponderosa Pine Forests?

Stand structures and the silvicultural activities used to create and maintain these structures are grounded in forest management objectives. As these objectives have shifted over recent decades, there has been renewed interest in multi-aged management in ponderosa pine forests. Across land ownerships in the U.S., and especially on public lands, forest management objectives have diversified and shifted to include a greater emphasis on objectives such as conservation of biodiversity, recreation, and climate change mitigation, than was the case fifty years ago (e.g., Bradford and D’Amato 2012; McGinley et al. 2023). Pick up the current edition of any long-running silviculture textbook and notice the

chapters devoted to such subjects that were not present in editions from the 1980s (e.g., Ashton and Kelty 2018).

Ponderosa pine forests have a long history of use to meet varied objectives (Arno and Fiedler 2015; Morgan 1988), but the conversion of large areas to plantations and other high-yield, even-aged systems in response to booming timber demand following World War II narrowed this management focus (O'Hara 2005). This is not to say that even-aged systems of management are unable to meet a wide range of objectives, but that a primary focus on timber in many even-aged systems post-war tended to produce structures that were less suited to other objectives. Stands resulting from such management also diverge markedly in structure and function from the natural dynamics of ponderosa pine forests (Churchill and Larson 2023; D'Amato and Palik 2023). Multi-aged structures are both more consistent with the historical (pre-Euro American settlement) disturbance regime of most northern Rocky Mountain ponderosa pine forests and provide opportunities to satisfy many important contemporary management objectives in the ponderosa pine zone and beyond (e.g., Arno et al. 1995; Graham and Jain 2005; O'Hara 1998, 2014).

Management objectives with special resonance in ponderosa pine forests of the northern Rocky Mountains today include increasing the resilience to natural disturbances and climate change and providing aesthetic value (Fiedler and Arno 2015; Halofsky 2018; Smith and Arno 1999). As described elsewhere in this guide, frequent to moderately frequent fire and periodic bark beetle outbreaks are characteristic disturbances of northern Rocky Mountain ponderosa pine forests. Interaction of these disturbances with ponderosa pine's physical and physiological attributes contributed to



Figure I.2—Prescribed fire has been used to restore the structure and processes associated with a frequent-fire disturbance regime in this multi-aged ponderosa pine stand managed by The Nature Conservancy. For many stands, especially those on public lands, the structure displayed here may represent a desirable long-term goal of transformation (albeit one that will require many decades to approach). USDA Forest Service photo by Neil Williams.



Figure I.3—Although high dead fuel loads create conditions that are conducive to the kind of large, high-severity fires that degrade ecosystem resilience, low densities of large snags were typical of pre-settlement ponderosa pine forests (Fiedler and Arno 2015) and serve many ecological functions. USDA Forest Service photo by Neil Williams.

the development of stand structures that were commonly uneven-aged (e.g., Arno 1999; Fiedler and Arno 2015; Hood et al. 2021). Although climate change will alter the growing environment and disturbance regimes of northern Rocky Mountain ponderosa pine forests, these uneven-aged structures provide the best foundation for adaptive management to foster enduring resilience (Hessburg et al. 2015, 2019; Larson and Churchill 2012). In this sense, transformation to uneven-aged structures (a narrower scope than this report, which includes all multi-aged structures) may dovetail with the current scientific, management, and social interest in ecological restoration. Uneven-aged and two-aged structures have the additional advantage of maintaining continuous tree cover, which is central to the provision of aesthetic benefits valued by the public (e.g., O'Hara 2014; Powell 2018). In high-visibility locations, this may be fundamental to maintaining the social license for management activities on public lands (Fiedler and Arno 2015).

Box 1—Age-Class Structure Definitions

As we discuss further in Chapter 2, consistent use of a shared silvicultural terminology forms a bedrock for communication. Here, we briefly define the stand-scale age-class structures that will be referred to frequently in this guide. Chapter 2 provides further definitions of silvicultural practices in the context of activity reporting. In Chapter 4, box 4, we provide stand diameter distributions typical of each age-class structure. Definitions below are from The Dictionary of Forestry (Deal 2018) unless otherwise noted.

Cohort—A group of trees developing after a single disturbance, commonly consisting of trees of similar age, although it can also include a considerable range of tree ages.

Even-aged stand—A stand of trees composed of a single age class or cohort in which the range of tree ages is ± 20 percent of rotation.

Two-aged stand—A stand containing trees of two distinct age classes, each representing at least 20 percent of the canopy cover or basal area, separated in age by more than ± 20 percent of rotation.

Uneven-aged stand—A stand containing trees of three or more distinct age classes, either intimately mixed or in small groups.

Multi-aged stand—A stand containing two or more age classes or cohorts. Two-aged stands and uneven-aged stands are both examples of multi-aged stands.

Balanced uneven-aged stand—An uneven-aged stand in which all age classes occupy equal areas and their differences in age are a constant value, equal to the cutting cycle.

Unbalanced uneven-aged stand—An uneven-aged stand that is not balanced, i.e., one in which age classes do not occupy equal areas and/or the differences in age between age classes are not equal. Such a structure may also be described as “irregular”¹.

Silvicultural system—A planned series of treatments for tending, harvesting, and re-establishing a stand. The system name is typically based on the number of age classes or the primary regeneration method used.

Cutting cycle—The time between harvests in a multi-aged silvicultural system².

¹ Ashton and Kelty 2018

² O'Hara 2014

Although ponderosa pine forests are the focus of this document, the tendency for transformation to multi-aged structure to produce more complex stands than the initial even-aged starting condition—especially when this is a plantation—fits within a much broader ongoing conversation around increasing compositional and structural diversity in forest management, and the role of multi-aged approaches in this process (e.g., Franklin et al. 2018; O’Hara 1998; Palik et al. 2020; Pommerening and Murphy 2004; Puettmann et al. 2008).



Figure I.4—A dense infill of understory and midstory Douglas-fir (*Pseudotsuga menziesii*) in this mid-successional ponderosa pine stand threatens long-term resource sustainability. Stands in this condition are common in the northern Rocky Mountains, and are the target of management efforts to promote a more resilient, multi-aged, ponderosa pine-dominated structure. USDA Forest Service photo by Neil Williams.

Why Produce This Management Guide?

Silvicultural transformation is characterized by higher uncertainty and greater complexity than continuation of an existing silvicultural system (O’Hara 2014). Despite these obvious barriers

to implementing transformation to multi-aged structures, we are not aware of any comprehensive, accessible guidance on how to plan or carry out the process of transformation³.

As we describe elsewhere in this document, knowledge gained from practical experience of local conditions, species' silvics, and vegetation responses to treatment is invaluable when navigating the uncertainty associated with transformation from one age-class structure to another. However, we also believe there is a place for written guidance that targets the needs of practitioners. Our hope is that this document helps fill what we perceive as a gap in practical guidance on transformation to multi-aged structures in ponderosa pine stands. For some readers, the information provided in this document may be relatively new. For others, it may fill very specific knowledge gaps, or simply provide the confidence to trust one's instincts and existing knowledge. We attempt to provide for all these levels of existing knowledge and experience. A challenge with silvicultural transformation, as in so much of silviculture, is providing information that is sufficiently detailed, yet also flexible enough to accommodate major differences in site and stand conditions, management objectives, and resource constraints. We hope to strike this balance.

A more general challenge with transformation to multi-aged structures in ponderosa pine stands in the northern Rocky Mountains concerns the limited application of multi-aged management in the region. Limited use of multi-aged methods inevitably reduces opportunities for foresters to acquire the practical experience that is so valuable to mastering unfamiliar practices. The predominance of even-aged silviculture in ponderosa pine forests on large public and private ownerships in this region also reduces access to working examples of multi-aged management in ponderosa pine forests and the local experts that provide a focal point for community learning. In this context, the prospect of transformation from even-aged to multi-aged structures may, understandably, be formidable. Although this guidebook is skewed towards the transformation process, discussion of management options in Chapter 6 is also broadly applicable to sustained, multi-aged management of stands that have been transformed to the desired multi-aged structure.

The perception that multi-aged management is complex, rigid, and resource-intensive (Guldin and Baker 2006; O'Hara 2002; Powell 2018) may also deter the transformation to multi-aged structures. In this guide we illustrate the breadth of possible multi-

³ Although see O'Hara 2002 and 2014 for useful high-level and conceptual development of transformation, and journal articles by Schütz 2001 and Kelty et al. 2003 among others, for practical ideas on transformation in specific forest types.

aged structures suited to ponderosa pine and the diversity of management options for sustaining these multi-aged structures. While some of the silvicultural methods described in this guide may be relatively complex, others are not. We provide ideas for simplifying the process of transformation and subsequent multi-aged management and options for increasing management flexibility. By highlighting the variety and flexibility of multi-aged harvest methods and their potential value during and after silvicultural transformation in ponderosa pine stands, we hope that this guide will make the idea of multi-aged management less daunting and more compatible with the realities of on-the-ground forest management.



Figure I.5—Regeneration of a new cohort (right of image) following an irregular shelterwood harvest is the beginning of transformation to a multi-aged structure in this ponderosa pine stand. USDA Forest Service photo by Neil Williams.

Using This Management Guide—

Although this management guide may be of interest to a wide range of audiences, it was developed for the management community. We address some of the operational constraints that public and private land managers may face when attempting to implement multi-aged management. In places, we focus on the management of public land when discussing the transformation process. This simply reflects the significant proportion of ponderosa pine forests that are under public ownership in the northern Rocky Mountains and the close alignment between the multi-resource benefits provided by multi-aged structures and the multiple-benefit framing that is common in public land management. A wide range of multi-aged structures and silvicultural treatments have been used in ponderosa pine forests to satisfy diverse objectives, including timber production, livestock grazing, and providing wildlife habitat (e.g. Alexander 1986; Fiedler and Cully 1995; Shepperd 2003). Moreover, silvicultural practices developed over recent decades (e.g., variable density thinning,

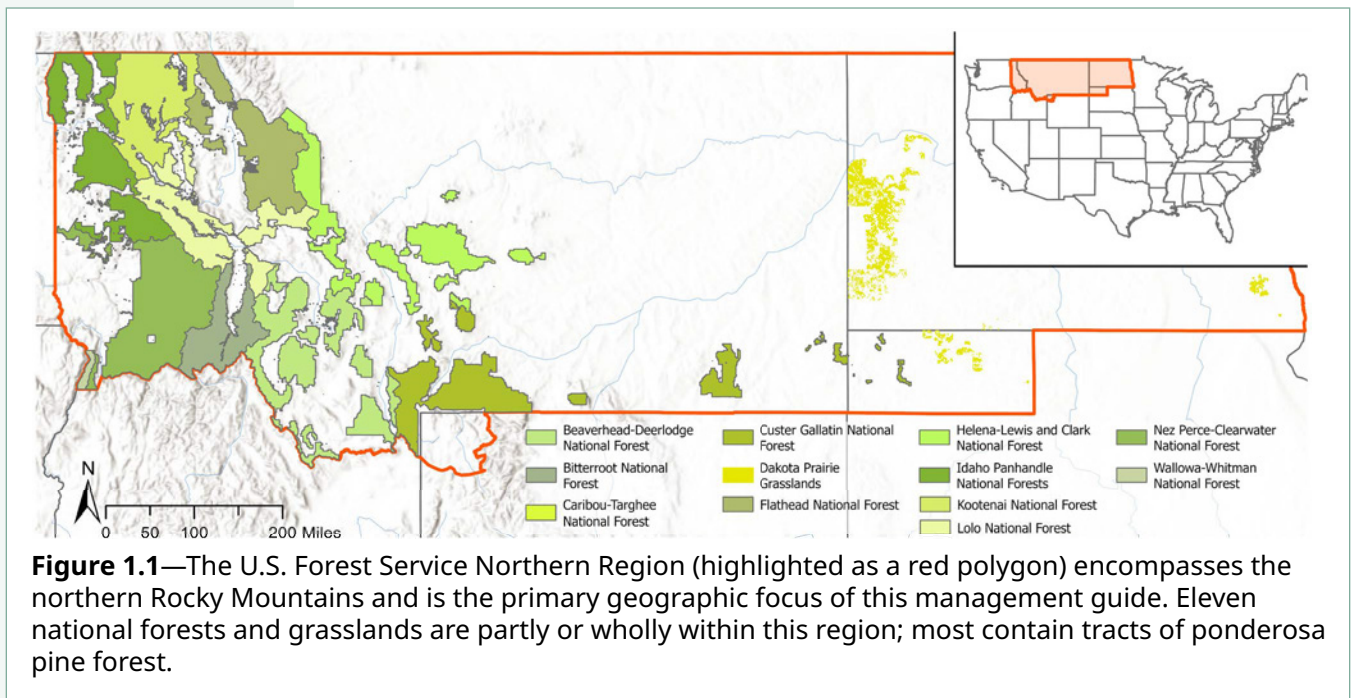
O'Hara et al. 2012; Palik et al. 2020), and older methods that have recently been re-popularized (irregular shelterwood, see Raymond et al. 2009; Seymour 2023) extend the management toolbox and accommodate different sets of management objectives or provide new ways of fulfilling management objectives. By covering these diverse practices, this guide is relevant to many different land ownerships and across different site types.

The content of this guide is structured around a *transformation framework* that describes key steps in planning the transformation from even-aged to multi-aged structures. Chapters 1 and 2 provide the biophysical and historical context for ponderosa pine forests and the management systems that have been used in these forests, as well as definitions of key management terminology used in this guide. The definitions in Chapter 2 provide an example of a crosswalk between many multi-aged silvicultural practices and codes used in the U.S. Department of Agriculture, Forest Service's FACTS (activity reporting) database. The transformation framework is described in Chapter 3, and key sections of this framework are reviewed in Chapters 4–6, the latter of which introduces management options for accomplishing the transformation to a multi-aged structure and for subsequent multi-aged management. Chapters 7 and 8 describe some hypothetical transformation sequences and real-world examples of ongoing transformations in ponderosa pine stands in the northern Rocky Mountains. Finally, Chapter 9 discusses some additional considerations relevant to multi-aged management of ponderosa pine stands.

Chapter 1: Context

Geographic Focus

The primary geographic focus of this management guide is the northern Rocky Mountains of the United States (fig. 1.1). As described below, ponderosa pine is a widely distributed species with a range that extends from British Columbia to Mexico and from the Great Plains to the Pacific Coast. Across much of this range, ponderosa is an iconic species of great cultural and economic importance. Nowhere is this truer than in the northern Rocky Mountains, which encompasses Montana and northern Idaho. Ponderosa pine has immense significance to Indigenous populations in this region (e.g., Östlund et al. 2005) and has provided a foundation for Euro-American settlement from the 19th century onwards (Fiedler and Arno 2015). Much research on the ecology and management of ponderosa pine has originated from the northern Rocky Mountains.



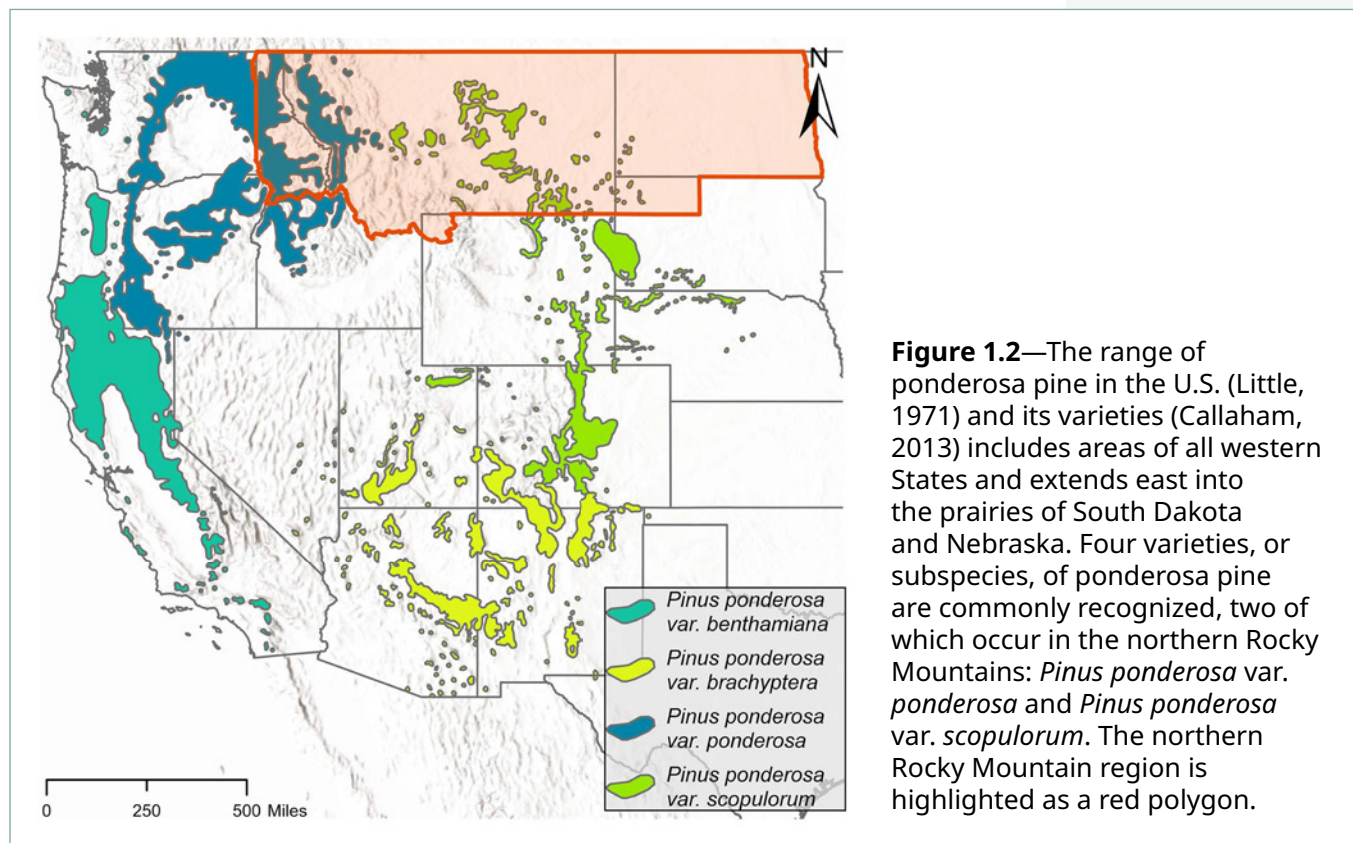
For the purposes of this management guide, we define the northern Rocky Mountain region as the area within the Northern Region of the United States Department of Agriculture, Forest Service (hereafter Forest Service). Although the northern Rocky Mountains are the primary focus of this management guide, much of the material that we present will be broadly applicable throughout the range of ponderosa pine. This includes the framework for silvicultural transformation that is central to this guide, as well as the management options that are described in Chapter 6. Therefore, while this publication will be of particular relevance

within the Northern Region, it is also relevant to the management of ponderosa pine forests elsewhere.

Biogeographic Context for Northern Rocky Mountain Ponderosa Pine Forests

Geographic distribution—

Ponderosa pine is among the most widely distributed conifers in the United States (Oliver and Ryker 1990). It is the dominant species in forests covering more than 27 million ac (11 million ha) of the U.S. and is a minor species in an additional 13.6 million ac (5.5 million ha) of forestland (Van Hooser and Keegan 1988). Ponderosa pine forests are a feature of all western U.S. States, and ecologically and economically important populations of the species also occur in the Black Hills of South Dakota, extending east into the Sandhills prairie of western Nebraska (fig. 1.2).



Two of the four commonly recognized varieties of ponderosa pine are present in the northern Rocky Mountains (fig. 1.2). *Pinus ponderosa* var. *ponderosa* (commonly referred to as Pacific or Columbia ponderosa pine) is found in the interior northwest, including northern Idaho and northwestern Montana, while *Pinus ponderosa* var. *scopulorum* (Rocky Mountain ponderosa pine) occurs primarily to the east of the Continental Divide in Montana

(Fryer 2018; Howard 2003). Although certain physiological differences between Pacific and Rocky Mountain ponderosa pine are relevant to silviculturists, as are differences in the climate of sites supporting Pacific and Rocky Mountain ponderosa pine, the two varieties share key functional traits controlling responses to silvicultural treatment and are united by a common silvicultural context (Fryer 2018; Howard 2003; Shepperd and Battaglia 2002). For these reasons, we do not differentiate between Pacific and Rocky Mountain ponderosa pine in this guide, unless explicitly stated.

Climate and site—

Ponderosa pine is among the most drought-tolerant species in the western U.S. and is competitive on sites with widely varying soil moisture regimes (Oliver and Ryker 1990; Pfister et al. 1977). In the northern Rocky Mountains, the species occupies sites to the east of the Continental Divide receiving less than 12 inches (305 mm) in total annual precipitation (Pfister et al. 1977). It is also present alongside western redcedar (*Thuja plicata*) on sites in northern Idaho that receive 88 inches (2,235 mm) (fig. 1.3). This broad ecological amplitude is particularly clear in the northern Great Plains, where ponderosa pine is often the dominant tree species on dry upland sites, but it also occupies regularly waterlogged riparian black cottonwood (*Populus balsamifera* subsp. *trichocarpa*) bottomlands (Fiedler and Arno 2015).

Mean annual temperature on sites occupied by ponderosa pine ranges from 41 to 50 °F (5 to 10 °C) (Oliver and Ryker 1990). In the northern Rocky Mountains, average January minimum temperatures on ponderosa pine sites may range from -1 to 31 °F (-18 to -1 °C), while average July maximum temperatures range from 57 to 94 °F (14 to 34 °C) (fig. 1.3).

Across its range, ponderosa pine grows at elevations from sea level to more than 10,000 ft. (3,000 m). In the northern Rocky Mountains, the species occupies sites ranging from 1,000–6,000 ft. (300–1,830 m) (Oliver and Ryker 1990).

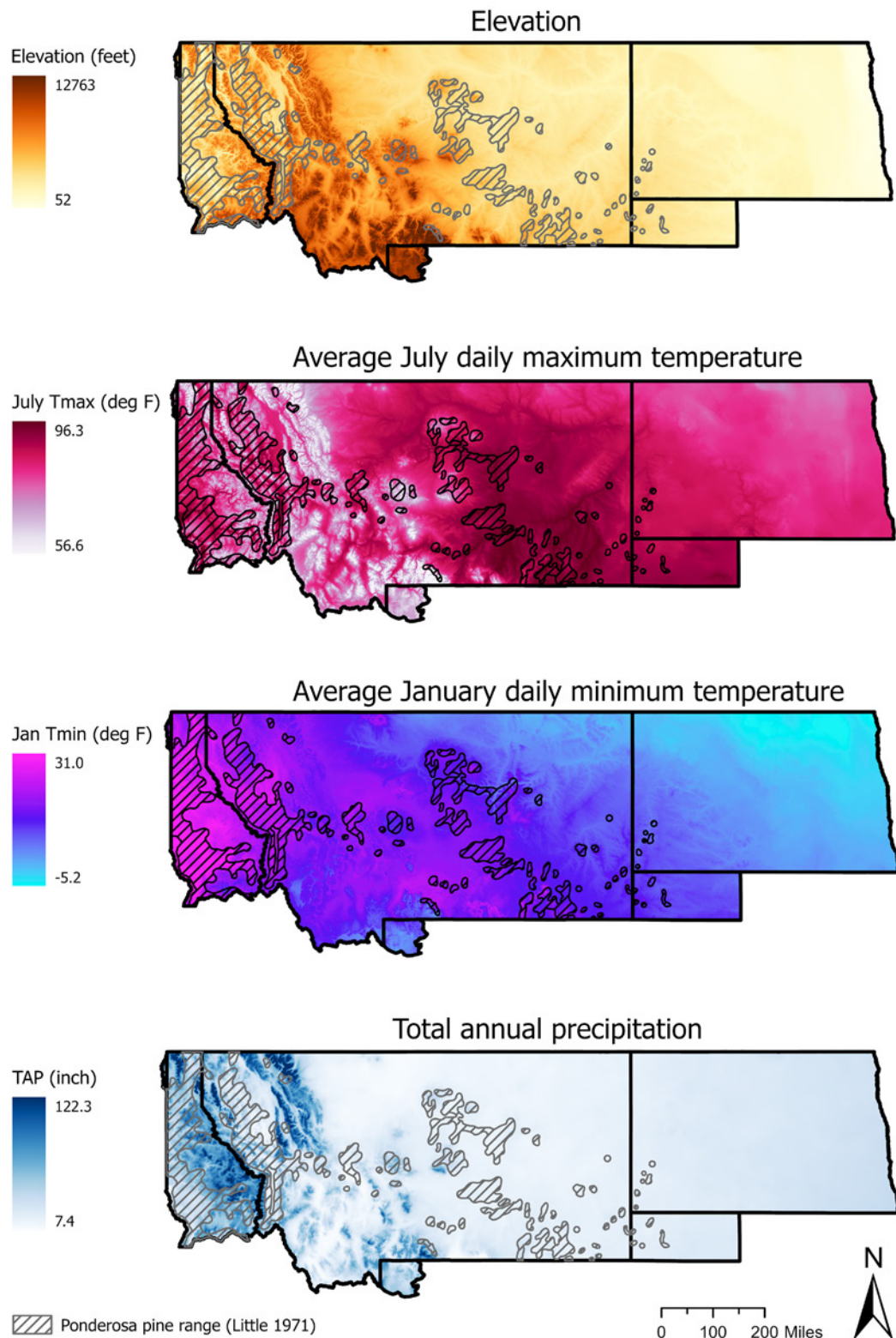


Figure 1.3—Elevation (source: LANDFIRE) and 30-year average total annual precipitation, and January minimum and July maximum temperatures (source: PRISM Climate Group) for the U.S. Forest Service Northern Region. July Tmax - mean daily maximum temperature for the month of July, Jan Tmin - mean daily minimum temperature for the month of January, TAP - total annual precipitation (including snow and rainfall).

In the *Pseudotsuga menziesii* and *Abies grandis* habitat type series, frequent fire helps perpetuate ponderosa pine in the overstory, while fire exclusion has the reverse effect.

Habitat types—

Habitat types are delineated based on the expected dominant overstory and understory species on a given site in the absence of disturbance (i.e., late-successional species) and are the most used potential vegetation classification system in the northern Rocky Mountains (Pfister et al. 1977). In this typology, individual habitat types are nested within habitat type series, which are named for the expected dominant late-successional tree species. Reflecting its broad ecological tolerances, ponderosa pine is the dominant late-successional tree species on habitat types in the *Pinus ponderosa* series and is an important seral component throughout much of the *Pseudotsuga menziesii* (Douglas-fir) and *Abies grandis* (grand fir) series (table 1.1). In the latter two habitat type series, frequent to moderately-frequent fire helps maintain ponderosa pine dominance in the overstory, arresting succession to dominance by late-successional species, while fire exclusion has the reverse effect (Arno 1980; Arno et al. 1995).

Table 1.1—Common associates of ponderosa pine (PIPO – *Pinus ponderosa*) in the Northern Rocky Mountain habitat types (Pfister et al., 1977) in which ponderosa pine may be an important component are: JUSC – *Juniperus scopulorum*, PSME – *Pseudotsuga menziesii*, ABGR – *Abies grandis*, LAOC – *Larix occidentalis*, PICO – *Pinus contorta*. Species' importance notation follows Pfister et al. (1977): S – major seral species, s – minor seral species, C – major climax species, c – minor climax species, () – dependent on location and/or habitat type phase, - = Not applicable.

Habitat type	JUSC	PIPO	PSME	ABGR	LAOC	PICO
<i>Pinus ponderosa</i> / <i>Andropogon</i> spp.	c	C	-	-	-	-
<i>Pinus ponderosa</i> / <i>Agropyron spicatum</i>	(c)	C	-	-	-	-
<i>Pinus ponderosa</i> / <i>Festuca idahoensis</i>	-	C	-	-	-	-
<i>Pinus ponderosa</i> / <i>Purshia tridentata</i>	(c)	C	-	-	-	-
<i>Pinus ponderosa</i> / <i>Symphoricarpos albus</i>	-	C	-	-	-	-
<i>Pinus ponderosa</i> / <i>Prunus virginiana</i>	-	C	-	-	-	-
<i>Pseudotsuga menziesii</i> / <i>Agropyron spicatum</i>	(c)	C	C	-	-	-
<i>Pseudotsuga menziesii</i> / <i>Festuca idahoensis</i>	-	-	C	-	-	-
<i>Pseudotsuga menziesii</i> / <i>Festuca scabrella</i>	-	C	C	-	-	-
<i>Pseudotsuga menziesii</i> / <i>Vaccinium caespitosum</i>	-	(S)	C	-	(S)	S
<i>Pseudotsuga menziesii</i> / <i>Physocarpus malvaceus</i>	-	(S)	C	-	(s)	(s)
<i>Pseudotsuga menziesii</i> / <i>Vaccinium globulare</i>	-	(S)	C	-	(S)	(S)
<i>Pseudotsuga menziesii</i> / <i>Linnaea boreallis</i>	-	(s)	C	-	(S)	(S)
<i>Pseudotsuga menziesii</i> / <i>Symphoricarpos albus</i>	-	(S)	C	-	-	(s)

Table 1.1 continued						
Habitat type	JUSC	PIPO	PSME	ABGR	LAOC	PICO
<i>Pseudotsuga menziesii</i> / <i>Calamagrostis rubescens</i>	-	S	C	-	(S)	(s)
<i>Pseudotsuga menziesii</i> / <i>Carex geyeri</i>	-	(s)	C	-	-	-
<i>Pseudotsuga menziesii</i> / <i>Spiraea betulifolia</i>	-	(S)	C	-	-	-
<i>Pseudotsuga menziesii</i> / <i>Arctostaphylos uva-ursi</i>	-	S	C	-	-	-
<i>Pseudotsuga menziesii</i> / <i>Juniperus communis</i>	-	-	C	-	-	S
<i>Pseudotsuga menziesii</i> / <i>Arnica cordifolia</i>	-	-	C	-	-	-
<i>Pseudotsuga menziesii</i> / <i>Symphoricarpos oreophilis</i>	(c)	-	C	-	-	-
<i>Abies grandis</i> / <i>Clintonia uniflora</i>	-	(S)	S	C	S	(s)
<i>Abies grandis</i> / <i>Linnaea borealis</i>	-	-	S	C	S	s
<i>Abies grandis</i> / <i>Xerophyllum tenax</i>	-	S	S	C	S	S

***Pinus ponderosa* series—**

The *Pinus ponderosa* series forms the lower tree line in much of the northern Rocky Mountain region and is typically bordered by grass-dominated communities at its downslope elevational limit. Sites in this habitat type series have lower soil moisture availability than any other forest type in the northern Rocky Mountains except the *Pinus flexilis* series, which may occur instead of *Pinus ponderosa* on extremely dry sites east of the Continental Divide. Elevations in the *Pinus ponderosa* series in the northern Rocky Mountains range from approximately 980 ft (300 m) to 5,400 ft (1,650 m), depending on location. Soils are variable but typically possess gravelly surface horizons (Pfister et al. 1977). Rocky Mountain juniper (*Juniperus scopulorum*) is the only other tree species to commonly reproduce in this vegetation series.

***Pseudotsuga menziesii* series—**

Occupying a broad elevation zone upslope of the *Pinus ponderosa* series (or forming the lower timberline in high-elevation valleys where the *Pinus ponderosa* series is absent) is the *Pseudotsuga menziesii* series (Pfister et al. 1977). This series may occur from approximately 2,000 ft (610 m) in northwestern Montana up to 8,000 ft (2,340 m) in southwestern Montana (Pfister et al. 1977). Sites in the *Pseudotsuga menziesii* series are typically well-drained, but soil types are highly variable and characterized only by their generally gravelly, acidic surface horizons. This broad range of site characteristics gives rise to substantial variability in understory plant composition in late-successional stands (table 1.1). Ponderosa pine, western larch (*Larix occidentalis*), and lodgepole pine (*Pinus*

contorta) are common seral tree species in the *Pseudotsuga menziesii* series, but Douglas-fir is the only tree species to reliably reproduce in late-successional stands in the absence of disturbance.

***Abies grandis* series—**

The habitat types in the *Abies grandis* series (Pfister et al. 1977) are found in areas with greater moisture availability than is typically present in the *Pseudotsuga menziesii* series. The geographic distribution of these sites loosely corresponds with the maritime-influenced climate of northern Idaho and northwestern Montana, and the *Abies grandis* series does not extend eastward of the lower Blackfoot and Bitterroot valleys of western Montana. The elevation of sites in this habitat type series is typically 2,400 ft (730 m) to 5,500 ft (1,670 m), depending on location. Soils are usually gravelly to silty loams, often derived from volcanic ash or loess (Pfister et al. 1977). Seral stands in the *Abies grandis* series may display high compositional diversity, including tree species with widely varying silvics.

While habitat types represent the potential vegetation on a site in the absence of disturbance, other vegetation classification systems delineate forest types based on the dominant existing vegetation. The Northern Region VMap project (Barber et al. 2011) uses this approach (fig. 1.4).

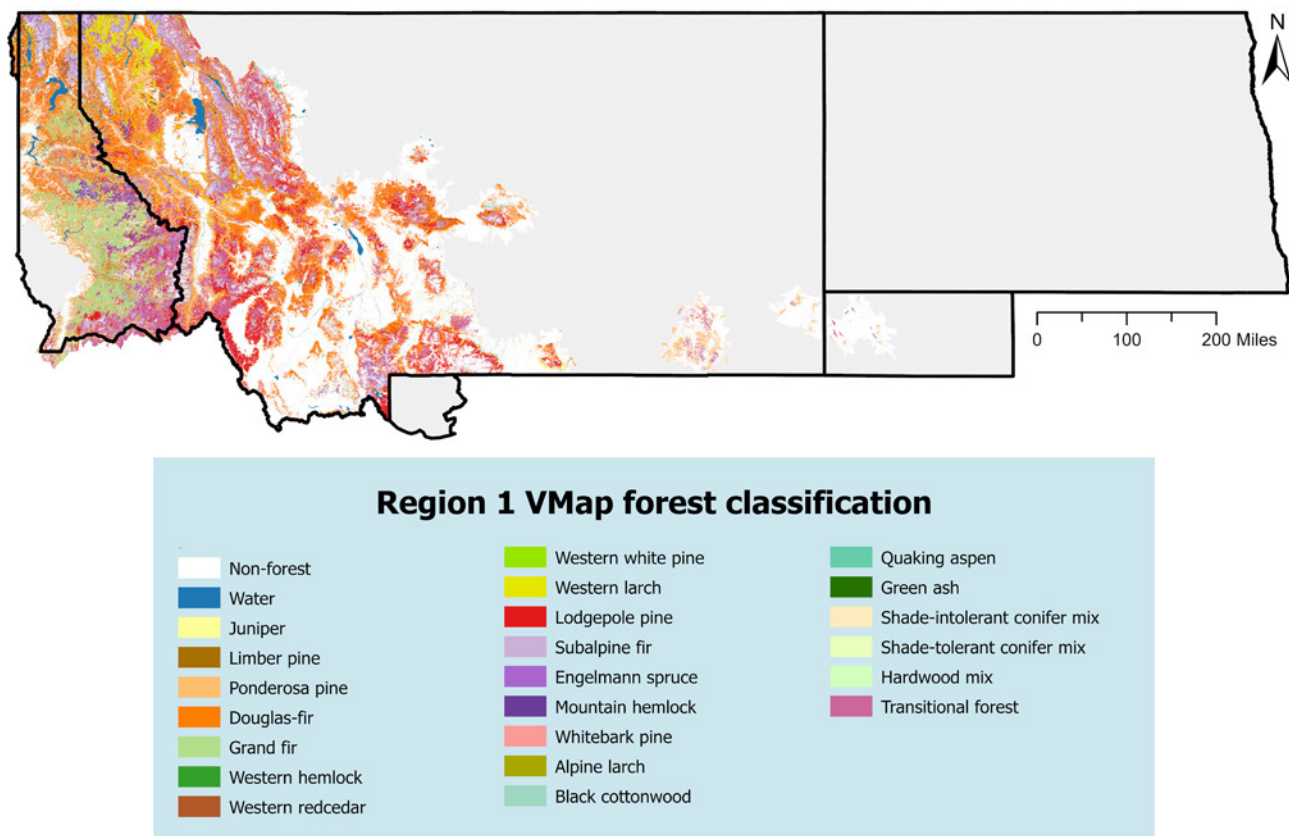


Figure 1.4—Existing vegetation in areas of the northern Rocky Mountains covered by the Region 1 VMap project (Barber et al. 2011). Forested vegetation classes identified on the map by species name represent forests in which the named species is the dominant tree species by canopy cover (i.e., relative canopy cover $\geq 40\%$). Mixed forest types (forests in which no single species has $\geq 40\%$ relative canopy cover) are divided between those dominated by shade intolerant conifers, shade-tolerant conifers and hardwoods.

Silvics—

Knowledge of species' silvics is key to perpetuating multi-aged stands and manipulating stand structure to favor target species over any species deemed less desirable for achieving management objectives. Although central to any silvicultural system, understanding the environmental tolerances of constituent tree species and their responses to competition and disturbance is arguably more important in multi-aged than even-aged systems. This is because of the wider range of environmental conditions experienced by different individuals throughout the stand (particularly between individuals in different canopy layers), and the need to successfully regenerate and maintain growth of younger cohorts, such that they can eventually replace the overstory (O'Hara 2014). Table 1.2 summarizes some important silvical attributes of common tree species in ponderosa pine forests of the northern Rocky Mountains.

Table 1.2—Key silvical attributes for ponderosa pine and four common associated species in ponderosa pine forests in the northern Rocky Mountains. Sources: 1 – Niinemets and Valladares, 2006; 2 - Hood et al., 2021; 3 – *Silvics of North America*; 4 – Fiedler and Arno, 2015; 5 – Aho, 1977, cited in The *Gymnosperm Database*; 6 – Jain et al., 2020, 7 – Hagle et al. (2003). a - wind is the primary dispersal mechanism for all species listed here.

Attributes	Ponderosa pine	Douglas-fir	Grand fir	Western larch	Lodgepole pine
Shade tolerance ¹	Low	Moderate	Very high	Low	Low
Drought tolerance ²	Very high	Moderate	Moderate	Moderate	Very high
Frost tolerance	Moderate	Low	Low	Moderate	High
Edaphic preference ³	Variable texture and origin	Variable texture and origin, but typically well-drained	Variable texture and origin	Deep, well-drained, variable origin	Variable texture and origin, rarely calcareous
Rooting habit ²	Deep	Usually deep	Variable	Deep	Deep
Longevity (years) ³	Typically 300 - 600, oldest > 950 ⁴	Typically 200 – 300, oldest > 700	Typically 250 – 300, oldest > 470 ⁵	Typically 300 – 500, oldest > 1,000	Typically 150 – 200, oldest > 400
Age to reproductive maturity (years) ²	10 - 20	12 – 15	20 – 50	25, heavier cone crops after 40	5 - 15
Seed periodicity ²	2 – 8	2 – 11	Several poor years follow good cone years	5	1 – 3
Seed dispersal distance ^{2 a}	50 % seeds > 80 ft; 20 % seeds > 195 ft	Mostly within 330 ft	Mostly within 330 ft	50 % seeds > 150 ft, 20 % seeds > 360 ft	50 % seeds > 65 ft; 20 % seeds > 150 ft
Seedbed preference ²	Mineral soil	Mineral soil, competitive advantage on duff ³	Flexible ⁶	Mineral soil, ash ⁶	Mineral soil
Fire resistance ²	Very high	High	Moderate	Very high	Low

Table 1.2 continued

Attributes	Ponderosa pine	Douglas-fir	Grand fir	Western larch	Lodgepole pine
Damaging agents: insects ⁷	Bark beetles in the <i>Dendroctonus</i> and <i>Ips</i> genus', especially <i>D. ponderosae</i> (mountain pine beetle), <i>D. brevicornis</i> (western pine beetle) and <i>I. pini</i> (pine engraver)	Douglas-fir beetle (<i>D. pseudotsugae</i>), Douglas-fir tussock moth (<i>Orgyia pseudotsugata</i>), and western spruce budworm (<i>Choristoneura fumiferana</i>).	Same as Douglas-fir, plus balsam bark beetle (<i>Dryocoetes confuses</i>), fir engraver (<i>Scolytus ventralis</i>), balsam woolly adelgid (<i>Adelges piceae</i>)	Few serious insect pests. Larch casebearer (<i>Coleophora laricella</i>) and western spruce budworm (<i>Choristoneura fumiferana</i>) reduce productivity	Many. Mountain pine beetle (<i>Dendroctonus ponderosae</i>) and pine engraver (<i>Ips pini</i>) are responsible for most extensive mortality.
Damaging agents: pathogens ³	Root rots are the most serious fungal pathogens; dwarf mistletoe (<i>Arceuthobium campylopodium</i>)	Numerous heart and root rots (e.g., <i>Armillaria mellea</i> , <i>Phellinus weirii</i>); needlecasts; dwarf mistletoe (<i>Arceuthobium douglasii</i>)	Highly susceptible, particularly to Indian paint fungus (<i>Echinodontium tinctorium</i>)	Few serious fungal pathogens; dwarf mistletoe (<i>Arceuthobium laricis</i>)	Many, including stem cankers needlecasts and heart and root rots; dwarf mistletoe (<i>Arceuthobium americanum</i>)
Response to release ³	Good at any size and age	Good at any size and age	Good in pole-sized timber and larger for trees with vigorous crown	All size classes, but most effective before 50 years of age	Good in young trees, dependent on vigor in older trees

Disturbance regimes—

A *disturbance regime* summarizes the typical characteristics of disturbance events affecting a given ecosystem, and the degree of variability in these characteristics through time and space (Keane 2013). A disturbance regime may describe the agents (types) of disturbance, as well as the spatial (e.g., extent or area and shape or configuration of the affected area), and temporal properties (e.g., frequency of events, variability in frequency through time) of disturbance events and their magnitude (e.g., intensity, severity). In common with much of western North America, fire and insects are primary disturbance agents in ponderosa pine forests of the northern Rocky Mountains (Dante-Wood 2018; Keane et al. 2018). In this section, we briefly review key elements of these disturbance regimes in the region's ponderosa pine forests.

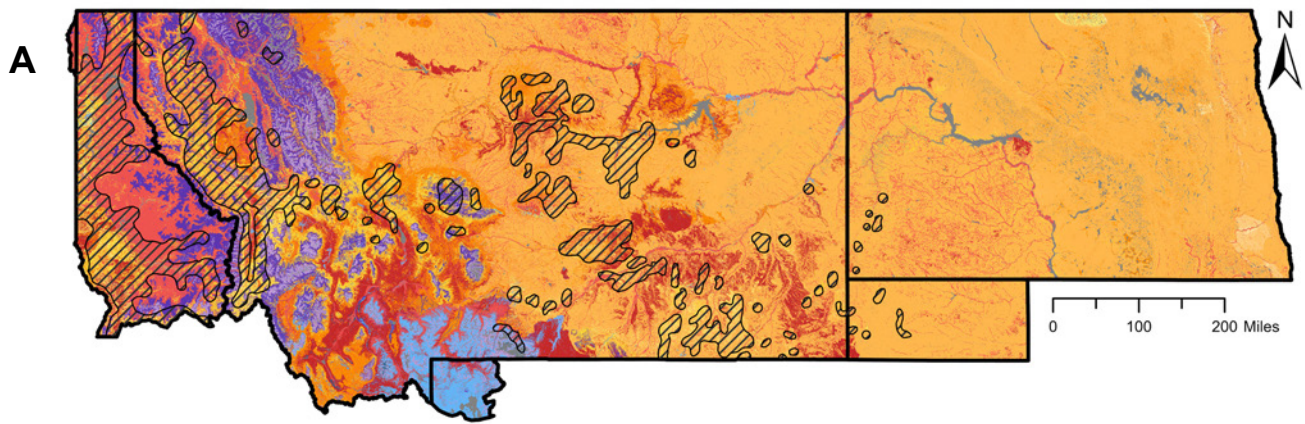
Fire—

Pre-settlement fire regimes of northern Rocky Mountain forests were shaped by vegetation, climate, topography, interactions with

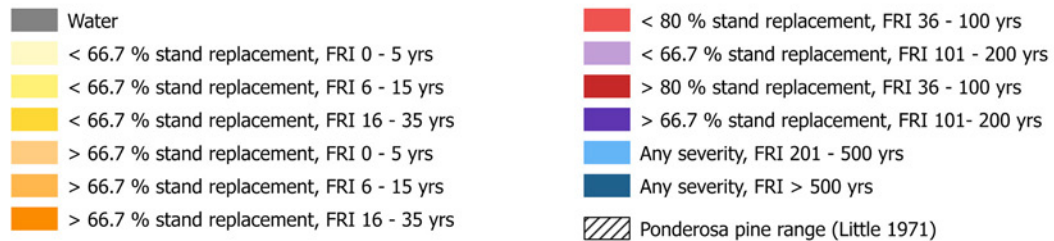
other disturbance agents, and burning practices of the Indigenous peoples native to this region (Arno 1980; Barrett et al. 1991; Hood et al. 2021). Fire activity influences the amount, structure, and spatial pattern of vegetation across the landscape, and in turn, feedback between fire and vegetation structure and the traits of constituent plant species influence fire behavior (Berkey et al. 2021; Stevens et al. 2020). As a result of this feedback, the distribution of forest habitat types across the landscape is aligned with the distribution of fire regimes. This relationship is imperfect because of other factors influencing fire occurrence and behavior at various spatial scales (Arno 1980) (fig. 1.5).

Low-elevation forests in the *Pinus ponderosa* series are associated with a high-frequency, low-severity fire regime (Hood et al. 2021). Average fire return intervals of 3–30 years have been reported for sites in this series in the northern Rocky Mountains, and relatively low-intensity surface fires made up a significant portion ($\geq 60\%$) of all burns (Arno 1980; Arno et al. 1997). On sites at the lower end of the fire return intervals, fire activity was likely driven by Indigenous burning (NatureServe 2018). High-severity fire was not absent from these forests, but affected small proportions of the landscape, occurred in small patches, and was extremely infrequent (e.g., return intervals of 100–300+ years) (NatureServe 2018 and references therein).

Low-intensity surface fires were also extremely common in the moister *Pseudotsuga menziesii* series, particularly on drier sites within the series. Fire return intervals have been estimated at 10–50 years across a range of site types (Arno 1980; Arno et al. 1995, 1997). At the upper end of this range, a mixed-severity fire regime characterized by variability in fire intensity and severity at fine spatial scales, was likely more common than the frequent low-intensity fires of the *Pinus ponderosa* series. Frequent to moderately frequent fire in both the *Pinus ponderosa* and *Pseudotsuga menziesii* habitat type series inhibited advancement to successional climax by maintaining a relatively open forest, often uneven-aged, in which large ponderosa pine and, in the *Pseudotsuga menziesii* series, western larch, were dominant overstory components (box 2) (Arno et al. 1995, 1997). High-intensity, stand-replacing fires are thought to have been more important on mesic sites in the *Pseudotsuga menziesii* series, sometimes producing two-aged or largely even-aged structures with a significant western larch component (Arno et al. 1997).



LANDFIRE fire regime groups



B

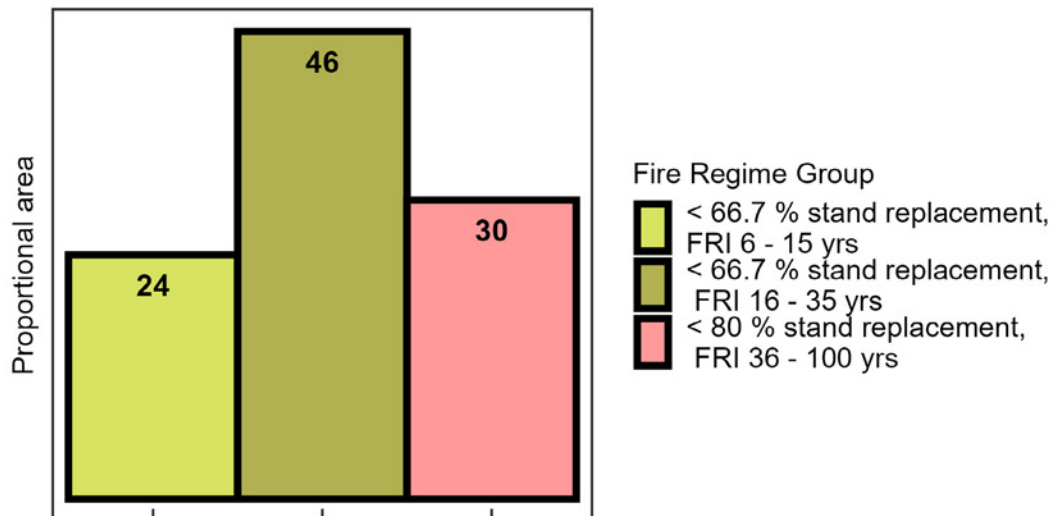


Figure 1.5—Using a combination of remote sensing and the “ecological systems” vegetation classification of NatureServe (NatureServe 2018), the LANDFIRE program has developed modeled, pre-Euro-American settlement fire regimes for vegetation types. (A) The modeled “fire regime groups” for the ecological systems of the northern Rocky Mountain region. These fire regime groups are described using the proportion of area that would be expected to experience high-severity (stand-replacing) fire, and by the fire return interval (FRI), a measure of fire frequency. The generalized range of ponderosa pine (Little 1971) is overlain on this map as cross-hatched polygons. This range is a coarse-scale approximation, and at finer spatial scales these polygons include vegetation types in which ponderosa pine is not present. (B) Summary of the relative importance of fire regime groups for the ecological systems within the range of ponderosa pine, in which ponderosa pine is commonly a major or minor component. The ecological systems comprising most of the area of each fire regime group shown in (B) are listed in (C), with a crosswalk to the habitat type series of Pfister et al. 1977.

C

Fire regime group	Dominant ecological systems ^a	Northern Rocky Mountain habitat type series
< 66.7 % stand replacement, FRI 6 – 15years	Northern Rocky Mountain Ponderosa Pine Woodland and Savanna	<i>Pinus ponderosa</i>
	Northwestern Great Plains-Black Hills Ponderosa Pine Woodland and Savanna-Savanna	<i>Pinus ponderosa</i>
< 66.7 % stand replacement, FRI 16 – 35 years	Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest-Ponderosa Pine-Douglas-fir	<i>Pseudotsuga menziesii</i>
< 80 % stand replacement, FRI 36 – 100 years	Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest-Grand Fir	<i>Abies grandis</i>
	Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest-Larch	<i>Pseudotsuga menziesii</i>

a For each fire regime group, dominance is assessed on an area basis. Hence, the ecological systems listed here represent the bulk of the total area of forest in which ponderosa pine is a component for each of the stated fire regime groups.

Figure 1.5—Using a combination of remote sensing and the “ecological systems” vegetation classification of NatureServe (NatureServe 2018), the LANDFIRE program has developed modeled, pre-Euro-American settlement fire regimes for vegetation types. The ecological systems comprising most of the area of each fire regime group shown in (B) are listed in (C), with a crosswalk to the habitat type series of Pfister et al. 1977.

Although less is known about pre-settlement fire regimes in the *Abies grandis* series, these sites probably experienced greater variability in fire intensity and severity than is the case for drier, lower-elevation habitat types (Arno 1980; Hood et al. 2021). The result is a mixed-severity fire regime involving low-, moderate- and high-severity patches in close spatial association, producing heterogeneous stand structures. Existing evidence suggests that median fire return intervals for sites at the drier end of the *Abies grandis* series were 10–50 years, increasing to 70–250 years on wetter sites (Arno 1980; Arno et al. 1995; Naficy 2017). These differences in fire regime were likely reflected in differences in forest structure. Shorter fire return intervals favored shade-intolerant, fire-tolerant species—notably ponderosa pine and western larch (box 2)—and longer return intervals favored succession to denser forests dominated by late-successional species, including grand fir (Arno 1980). However, the importance of disturbance—fire, diseases and insect pests—is such that large patches of closed-canopy forest were probably relatively rare and seldom attained 100 percent canopy cover, even on the most mesic sites (NatureServe 2018).

Box 2—Ponderosa pine, fire, and western larch

As we have discussed, ponderosa pine is among the most fire-tolerant trees in western North America. In the northern Rocky Mountains, the range of ponderosa pine overlaps with that of western larch, a conifer with even greater resistance to fire. And, like ponderosa pine, past exploitative logging and 20th century fire suppression have reduced the landscape-scale abundance of large individual larch trees and stands dominated by large, sawtimber-sized larch. As a result, larch is also a target of restoration efforts aiming to increase forest resilience by recruiting populations of the large, fire-resistant conifers that were once important structural anchors in dry and moist mixed-conifer forests.

Fortunately, while larch lacks the extreme drought tolerance of ponderosa, the shared fire tolerance, shade intolerance, and longevity of these species facilitates managing for these two conifers in mixed species stands on mid-elevation sites in the *Pseudotsuga menziesii* and *Abies grandis* habitat type series. In this management guide we commonly feature western larch alongside ponderosa pine in examples of management approaches to foster multi-aged stands dominated by these two iconic, fire-dependent conifers.

At the landscape-scale, spatial variability in fire activity contributed to the development of a fine- to coarse-grained spatial mosaic of vegetation that is characteristic of many interior western conifer forests (e.g., Arno 1980; Hagmann et al. 2013; Hessburg et al. 2005). Viewed at relatively small spatial scales (e.g., 0.5–2.0 ac), frequent, low-severity fire on drier sites produced a heterogeneous structure characterized by the presence of individual trees, tree clumps of varying size, and gaps (also referred to as mosaic-meadows (Matonis and Binkley 2018) and typically irregularly-shaped) (e.g., Churchill et al. 2017; Larson and Churchill 2012). Viewed at larger spatial scales (e.g., 2–1,000 ac), replication of this pattern forms a fine-grained mosaic (Hessburg et al. 2015, 2019) with relatively low spatial variability. By contrast, the small to moderately-sized patches of moderate- and high-severity fire that occurred on mesic sites in the *Pseudotsuga menziesii* and *Abies grandis* series produced two-aged to even-aged patches that, at larger spatial scales, create a coarser, more varied mosaic (Hessburg et al. 2015, 2019). Variability in this mosaic structure was most pronounced in areas of the landscape with heavily dissected topography, where environmental gradients drive spatial variability in vegetation type and potential fire behavior (Hood et al. 2021).

Burning by Indigenous populations in the northern Rocky Mountains substantially modified fire activity, with important consequences for ecosystem structure (Kimmerer and Lake 2001; Östlund et al. 2005). Lighting fires for foraging, ceremonial, defensive, or other purposes increased fire activity on the

Vegetation composition and structure on many habitat types in which ponderosa pine is present in the northern Rocky Mountains has now departed from the conditions thought to exist before Euro-American settlement.

landscape beyond that caused by lightning ignitions. The human-ignited fires were concentrated in certain areas, rather than the more random spatial pattern of lightning ignitions (Fiedler and Arno 2015). Indigenous burning was particularly frequent in areas that served as travel corridors and helped to arrest successional dynamics. This maintained forests in more open conditions dominated by shade-intolerant, but fire-tolerant species than would have been the case under a lightning-driven ignitions regime (e.g., Arno et al. 1997; Östlund et al. 2005).

The forced cessation of Indigenous burning and the exclusion of lightning-ignited fires under 20th and 21st century fire suppression policies, along with grazing and historical high-grading of large, fire-resistant trees (including ponderosa pine) have had profound and well-documented effects on ponderosa pine forests and other mixed-conifer forests of western North America (e.g., Agee 1993; Hagmann et al. 2021; Merschel et al. 2021; North et al. 2022). In the absence of frequent fire, stand density in many of these forests has greatly increased due to ingrowth (e.g., Clyatt et al. 2016; Crotteau et al. 2018; Stephens et al. 2015). Although this densification is sometimes the result of ponderosa pine thickets that would have been thinned by fire (Larson and Churchill 2012), much ingrowth results from the prolific regeneration and growth of more shade-tolerant species (principally Douglas-fir and grand fir in the northern Rocky Mountains) (Arno et al. 1997; Battaglia et al. 2007; Churchill et al. 2017; Johnston 2017).

Thus, on many sites, species composition has shifted away from seral fire-tolerant species—ponderosa pine and western larch—to more shade-tolerant species that have lower fire tolerance for part or all their lifespan (e.g., Arno et al. 1995; Rodman et al. 2021; Stevens et al. 2020). Because of these changes, vegetation composition and structure in many habitat types where ponderosa pine is present in the northern Rocky Mountains has departed from the conditions thought to exist before Euro-American settlement (fig. 1.6). These changes in structure, composition, and disturbance processes have marked and diverse effects on ecological functions (e.g., habitat, nutrient cycling, snow retention) as well as increasing disturbance and mortality risks (e.g., Graham and Jain 2005; Hessburg et al. 2005; Long and Smith 2000; Stephens et al. 2015, 2017).

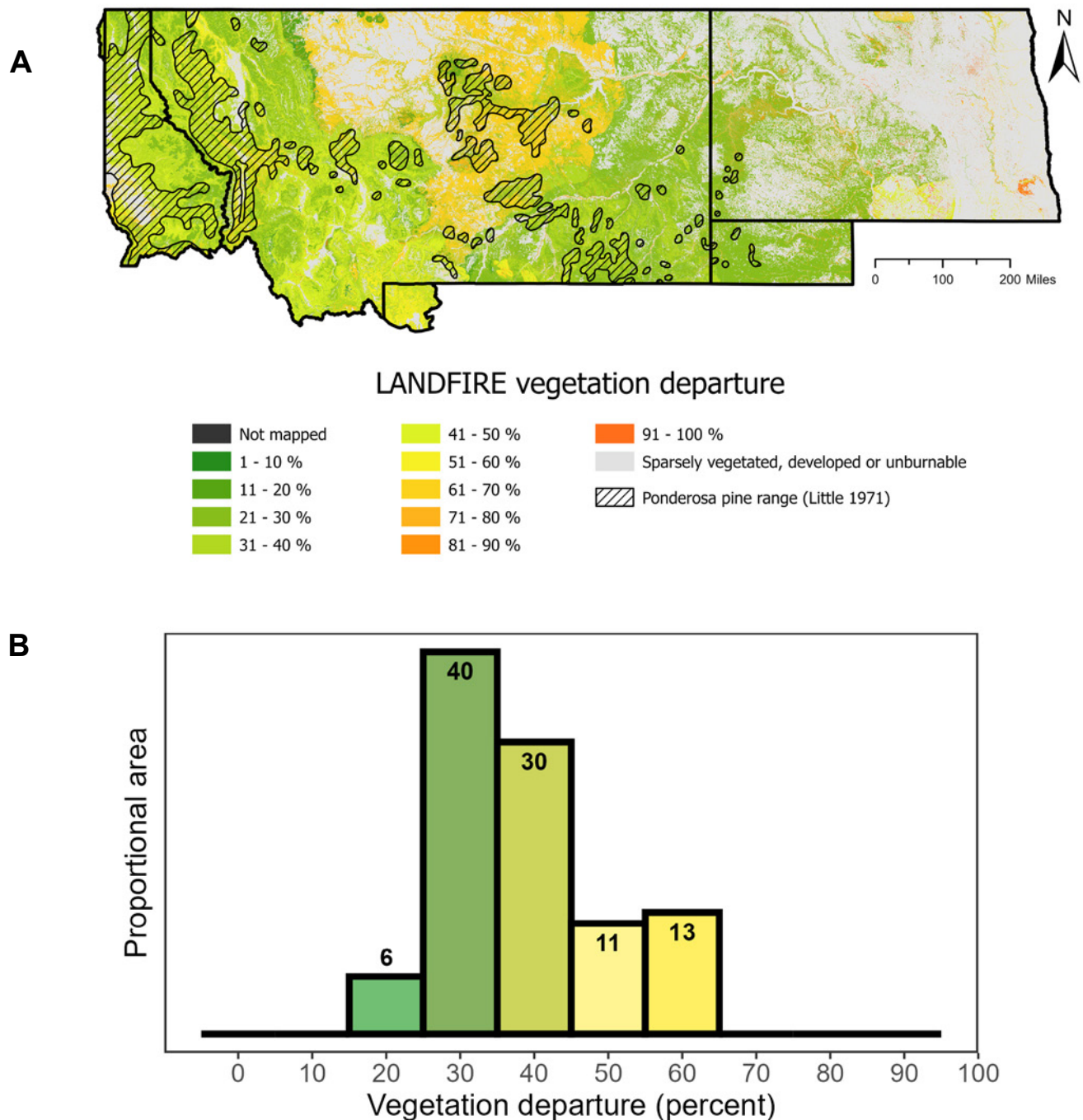


Figure 1.6—Across large areas of the western United States, current vegetation structure has departed from the assumed pre-Euro American settlement conditions. One metric of this change is the LANDFIRE vegetation departure index, shown in Figure 1.6 (a) for the northern Rocky Mountain region. Expressed as a percentage, the vegetation departure index represents the modeled difference between current vegetation structure and the simulated pre-Euro American settlement vegetation structure (source: LANDFIRE). The generalized range of ponderosa pine (Little 1971) is overlain as cross-hatched polygons. Figure 1.6 (b) shows the vegetation departure, by proportional area, for the northern Rocky Mountain NatureServe ecological systems (NatureServe 2018) within the range of ponderosa pine in which ponderosa pine is commonly a major or minor component.

Insects—

Insect pests are integral to the ecology of ponderosa pine forests, directly influencing forest structure and dynamics and indirectly altering numerous ecosystem functions, from carbon storage and nutrient cycling to wildlife habitat (Edburg et al. 2012; Fiedler and Arno 2015; Graham et al. 2019; Saab et al. 2014). At least 108 insect species are known to predate on Pacific ponderosa pine, and 59 of these species attack Rocky Mountain ponderosa pine, including bark beetles, shoot and bud miners, and defoliators (Oliver and Ryker 1990). Direct effects on ponderosa pine trees range from reductions in vigor, seed production, or regeneration success, to mortality at scales ranging from individual trees to landscapes (Loehman et al. 2018; Shaw et al. 2022). However, even those insects capable of causing large-scale mortality episodes are typically present at endemic (background) levels, causing little to no mortality until favorable conditions enable eruptive population growth and trigger major host-tree mortality (Fettig et al. 2022; Wallin et al. 2008). This endemic-epidemic behavior is characteristic of the beetles in the *Dendroctonus* and *Ips* genera that are the dominant causes of ponderosa pine mortality in the northern Rocky Mountains (e.g., Dante-Wood 2018; Ryan et al. 2015).

Historically, mountain pine beetle (*Dendroctonus ponderosae*) has been the most destructive insect pest of ponderosa pine in the northern Rocky Mountains (USDA FHP 2024), although western pine beetle (*Dendroctonus brevicomis*) can cause heavy mortality to the west of the Continental Divide and *Ips* species, including pine engraver (*Ips pini*), are important secondary pests (Dante-Wood 2018; Keane et al. 2018; Oliver and Ryker 1990). In both endemic and epidemic stages, mortality has pronounced consequences for forest structure by altering species and size-class distributions as well as reducing stand density and creating gaps of varying size (see Chapter 9) (Fiedler and Arno 2015; Negrón et al. 2008). At endemic levels, mountain pine beetle attacks typically occur in individual or small clusters of mature trees, focusing on trees with a diameter at breast height⁴ (d.b.h.) of at least six inches (15 cm) (Alexander 1986; Fettig et al. 2022). During epidemics, these host size preferences may weaken as beetle numbers rise and they increasingly attack larger groups of trees of different sizes (Alexander 1986).

As with fire, the historic timing and periodicity of bark beetle epidemics in northern Rocky Mountain ponderosa pine forests has climate linkages. In parts of the southern Rocky Mountains, mountain pine beetle epidemics have been reported with an

⁴ Diameter at breast height (d.b.h.) is 4.5 ft (1.37 m).

approximate 20-year periodicity (Battaglia and Shepperd 2007), but prolonged warmth and lower than average moisture availability influence the specific timing of eruptive population behavior. Two mechanisms are particularly important. First, warmer temperatures are more conducive to beetle overwintering and reproduction rates in adults, thereby increasing bark beetle pressure on forests (Bentz et al. 2010; Loehman et al. 2018). Second, warmer, drier conditions reduce host-tree vigor, thereby reducing the capacity of hosts to manufacture the defensive compounds required to repel beetles and maintain respiratory demands under the combined strain of moisture and, potentially, heat stress (Creeden et al. 2014; Koontz et al. 2021; McDowell 2011). Stand density mediates this relationship between climate and bark beetle mortality through its effect on tree vigor (Fettig 2012; McDowell et al. 2006; Zausen et al. 2005). Together these factors help explain historic patterns of bark beetle epidemics and signal potential changes in bark beetle impacts on ponderosa pine forests as climate change progressively alters the growing environment (Anderegg et al. 2015; Fettig et al. 2013; Loehman et al. 2018).

Mortality caused by mountain pine beetle may have pronounced consequences for stand structure by altering species and size-class distributions, reducing stand density, creating open spaces of varying size and geometry, and altering dead fuel profiles.

History of Silviculture in Ponderosa Pine Forests of the Western United States

Knowledge of past management in ponderosa pine forests can inform future practice. The widespread application of even-aged silviculture in ponderosa pine today contributes to a belief that this is how ponderosa must be managed. In fact, the history of Euro-American management of ponderosa pine forests provides examples of a wide range of silvicultural systems, including both even- and multi-aged (Alexander 1986; Schubert 1974; Youngblood 2005). Understanding this history can help make sense of some contemporary management constraints, guide improvements in practice, and provide ideas to better align practice with emerging climate and disturbance risks.

We catalog four phases in the management of ponderosa pine forests after Euro-American settlement. However, for centuries to millennia before this, Indigenous people maintained ponderosa pine forests in the northern Rocky Mountains using regular burning and other management practices that served diverse ecological, subsistence, and cultural purposes (Barrett and Arno 1982; Kimmerer and Lake 2001).

Phase 1: Early Euro-American settlement—

Ponderosa pine forests were hugely important for Euro-American settlers arriving in the western United States from the early 1800s onwards (Fiedler and Arno 2015). Forests dominated by ponderosa

pine were not only widespread, but were also relatively accessible, occupying the lower elevations and containing open understories (fig. 1.7) that permitted easy passage and provided forage for livestock. Harvest of these forests to support mining, homesteading, and railroad construction during the 1800s and the early 1900s (depending on location) was typically exploitative, and post-harvest residual density and structure was largely driven by local requirements and the means of extraction (Fiedler and Arno 2015; O'Hara 2005; O'Hara et al. 2010). Heavy “selective” cutting that amounted to high grading of the largest trees was common, but “clearfelling” also occurred (Fiedler and Arno 2015).



Figure 1.7—This 1897 image by explorer, forester and botanist, John Lieberg, depicts the relatively open-canopied ponderosa pine stands that Euro-American settlers could have encountered in Montana’s lower Montane zone.

Phase 2: Initiation of multi-aged silviculture—

Much of the initial harvest of western ponderosa pine forests predated the establishment of silviculture as a discipline in North

America (Fiedler and Arno 2015; Rutkow 2013). As knowledge of silvicultural practices developed in the early 1900s, silviculturists with the newly formed Forest Service began implementing various forms of selective cutting (forms of partial harvest that were typically opportunistic, with little thought for future regeneration) at locations such as Lick Creek, in western Montana (O'Hara 2005; Smith and Arno 1999).

Concerns over inadequate regeneration following heavy extractive harvesting also led to the establishment of the first research forest in the United States near Flagstaff, Arizona (Fort Valley Experiment Station, now known as Fort Valley Experimental Forest). At Fort Valley, methods for regenerating and improving ponderosa pine forests were studied (Fiedler and Arno 2015; Olberding 2000). Selective harvests in these early multi-aged stands were often heavy, removing upwards of 60 percent of merchantable volume to make the ventures financially viable (Meyer 1934; O'Hara et al. 2010). As much of the removed volume was in the best (typically the largest) trees, the result of these selective harvests was commonly more akin to high grading than a selection system as we know it today (O'Hara 2005; Smith 1972).

Working in the Pacific Northwest, Meyer (1934) provided an example of a selection system that retained 10–30 percent of merchantable volume, with re-entry envisaged in 40–75 years (O'Hara 2002). This was the advent of multi-aged selection systems in ponderosa pine and was made possible, in part, by the invention and increasingly widespread application of tractor logging in the 1920s and 1930s. This technology provided much needed silvicultural flexibility by increasing cost efficiencies (O'Hara et al. 2010).



Figure 1.8—Residual trees left after a maturity selection cutting on the Pringle Falls Experimental Forest, Oregon. Image dated 1951 (O'Hara 2010).

Building on this flexibility, two visions for multi-aged silviculture in ponderosa pine forests emerged in the 1930s and 1940s (O'Hara 2002; O'Hara et al. 2010). *Maturity selection* (fig. 1.8) was advanced by scientists at the Pacific Northwest Research Station, led by Thornton T. Munger, as a system for managing interior northwestern ponderosa pine (Munger 1941; Munger et al. 1936). Meanwhile, *improvement selection* (fig. 1.9) was proposed by Gus Pearson, Director of the Fort Valley Experiment Station (Pearson 1942; 1950). Although debate around these two variants of the selection system was heated, maturity and improvement selection have much in common (O'Hara 2002; 2005).



Figure 1.9—"Blackjack" pines retained during an improvement cutting at Fort Valley Experimental Forest are shown here in the foreground, with a dense thicket of seedlings and saplings behind (Pearson 1942).

Both maturity selection and improvement selection incorporate individual tree assessment for retention value using Keen's classification (or adaptations thereof) of ponderosa pine vigor (Keen 1936; 1943) (fig. 1.10), with the objective of bringing unregulated old-growth stands into a more productive, regulated condition. Converting old-growth stands in this manner was viewed a prudent step to reduce the risk of mortality caused by insect pests that were observed in stands with old timber (although in the case of bark beetles, elevated mortality risks were associated with tree size, rather than age). Maturity selection involved zero-margin cutting in which trees were evaluated and ranked on economic and biological (probability of future mortality) grounds, with the idealized harvest removing about 40 percent of the merchantable volume over 30-year cutting cycles (Munger 1941; Munger et al. 1936; O'Hara et al. 2010). Improvement selection placed greater emphasis on development of (1) "thrifty," fast-growing younger stems of good form, (2) removing all the larger and older cohorts, (3) intentionally killing unmerchantable young trees of poor vigor, and (4) reducing the density of the sapling layer (O'Hara et al. 2010; Pearson 1942, 1950). In practice, the differences between these two selection systems were probably as much a product of different regional contexts and site conditions as different silvicultural philosophies (O'Hara 2002; O'Hara et al. 2010). Moreover, the extent to which these selection systems were implemented beyond the research-oriented settings in which they were developed is uncertain.

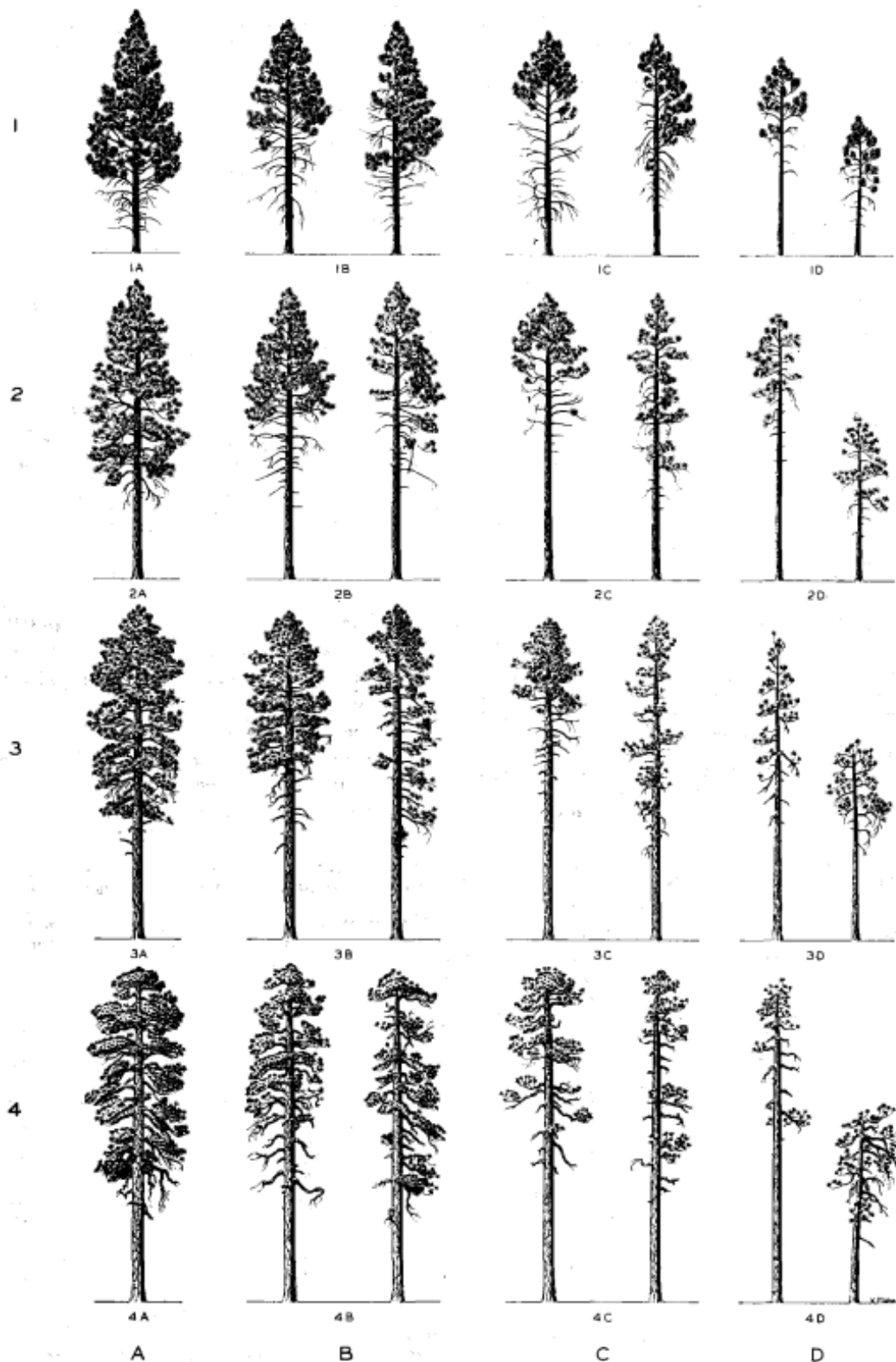


Figure 1.10—Keen's classification for ponderosa pine vigor was based on tree age and crown structure and served as the basis for early selection systems in ponderosa pine (Keen 1943). Within each age bracket (classes from 1 – 4, arranged vertically in this image), tree vigor declines from left to right based on crown structure (denoted using letters A – D). Low vigor trees identified using this classification were judged to be at higher risk of mortality from western pine beetle (*Dendroctonus brevicomis*).

Phase 3: Post-War increase in even-aged management—

In ponderosa pine forests, as in forests across the United States, the post-World War II era marked a shift toward even-aged management, including plantation silviculture (fig. 1.11) (Fiedler and Arno 2015). Factors behind this trend included (1) high nationwide demand for lumber to fuel post-war construction and the accompanying political pressure on the National Forest System to compensate for falling harvest volumes from cut-over private timberlands, and (2) over-application of uneven-aged management in forest types and sites for which it was not suited, accompanied by poor execution or planning of selection harvests on sites that could have been managed using well-thought-out multi-aged methods (Curtis 1998; Fiedler and Arno 2015; O'Hara 2002; Smith 1972). The predictably poor results of the second factor helped spur Forest Service policy toward greater use of even-aged methods by the mid-1950s (Isaac 1967; O'Hara 2002).

Clearcutting followed by planting was commonly used on private timberlands, and this practice spread to public lands as a means of boosting short-term harvest volumes to fulfill production obligations (Fiedler and Arno 2015). In the Blue Mountains of Oregon and Washington, *modified clearcutting* (essentially a form of liberation cutting) was used to convert old-growth stands into even-aged stands (Youngblood 2005). All overstory trees were felled and the advanced regeneration accumulated during fire exclusion was subsequently managed to a target density. These methods were economically efficient and perceived to minimize risks to growing stock from bark beetles.

A notable and controversial extension of the trend toward even-aged management in ponderosa pine forests was the experimentation with terracing and planting that occurred on several national forests. A particularly high-profile example of these practices was the clearcutting and terracing that occurred on the Bitterroot National Forest in



Figure 1.11—This ponderosa pine plantation in the Black Hills is managed in an even-aged system (image dated 1937). Courtesy photo by the Forest History Society, Durham, NC.

western Montana in the 1960s (Fiedler and Arno 2015; Swanson 2012) (fig. 1.12). Such intensive forms of even-aged management, implemented in highly visible locations, attracted widespread attention and heavily influenced public perceptions of even-aged management. This was despite the reality that even-aged systems do not need such singular focus on timber production using an agricultural model.



Figure 1.12—In some ponderosa pine forests, an intensive application of even-aged management involved clearcut or shelterwood harvests followed by terracing and planting, pictured here c. 1968. These practices sparked regional and national controversy, and contributed to debate within and beyond the forestry profession that ultimately led to passage of the 1976 National Forest Management Act. Courtesy image by the National Museum of Forest Service History.

Although such extreme practices were roundly criticized and fell into disuse, clearcutting in the absence of terracing had become widely employed in western ponderosa pine forests by the 1980s (Youngblood et al. 2005). There remained, however, regional variation in management approaches. In the northern Rocky

Mountains, interior Pacific Northwest, and California, clearcutting, often followed by planting, was favored; shelterwood and selection systems were also employed on sensitive sites (e.g., Barrett 1979; Foiles and Curtis 1973; Helms 1980). In the Colorado Front Range and the Southwest, regeneration challenges following clearcutting led to widespread application of two-stage shelterwood and group selection systems, except on sites with severe dwarf mistletoe infestation (Alexander 1986; Schubert 1974). Continuing a trend from the pre-war period, selection systems typically involved relatively low-intensity harvests (for example, removal of 30–40 percent of merchantable volume) and shorter cutting cycles (Alexander 1986; O'Hara 2005; Schubert 1974).

Phase 4: Re-Igniting interest in multi-objective management—

Ponderosa pine forests may be managed for many objectives, including provisioning (e.g., timber, forage), regulating (e.g., hydrological regulation), supporting (e.g., nutrient cycling), and cultural services (e.g., aesthetics, recreation) (Morgan 1988). Even before passage of the National Forest Management Act of 1976, tensions between maximizing short-term harvest volumes and satisfying objectives related to aesthetics and recreation in ponderosa pine forests materialized in public reaction to practices such as the terracing described above (Arno and Fiedler 2015). A consequence of the shift toward a broad multi-resource framing of forest management goals was renewed debate around the potential of multi-aged methods in and beyond ponderosa pine forests (e.g., Graham et al. 2006; Guldin and Baker 1998; O'Hara 1998). This debate focused not on whether even-aged practices were inappropriate for managing ponderosa pine (including plantation silviculture)—even-aged practices continue to be well-suited to some sites and management objectives—but rather to encourage broader consideration of the full suite of available management tools, from even-aged to two-aged and true uneven-aged methods.

In many western dry forests, debate around the merits of multi-aged management was paralleled by a growing interest in ecological restoration (e.g., Arno et al. 1996; Fiedler et al. 1999, 2010; Hessburg et al. 2015; Kolb et al. 2007) and fuels and fire hazard reduction (e.g., Hood et al. 2022a; Jain et al. 2012; McKinney et al. 2022; Peterson et al. 2005). However, application of ecological restoration and fuel reduction has often focused on short-term structural changes without clear concern for regenerating new cohorts or long-term stand dynamics (Covington et al. 1997; Hood et al. 2024). Silviculture provides the tools to achieve these restoration and fuel reduction challenges within a framing that expressly considers long-term sustainability of stand structures and resources—considerations that may be absent in management applications developed in other disciplines. In this

guide, we provide examples of opportunities for the development of silvicultural prescriptions capable of coherently integrating traditional silvicultural and restoration and fuels reduction perspectives to address diverse objectives.

Chapter 2: Terminology Used in This Guide

Terminology provides a foundation for technical discussion in any discipline. In silviculture, many practices are named based on effects (i.e., what happens in the forest) and intent (i.e., the silvicultural objective), producing a nuanced terminology that helps foresters navigate the important temporal dimension associated with forest management actions and forest development. Consistent application of this terminology improves clarity in documenting and communicating silvicultural actions through time, between practitioners, and in external reporting, for example in the silvicultural prescription, or in NEPA planning. Consistent use of common terminology is also advantageous in communicating and managing relations with external stakeholders, such as the public. Within the profession, use of shared terminology facilitates learning and sharing of best practices.

By contrast, “sloppy” use of terminology may create misunderstandings and has, on numerous occasions, led to inappropriate application of silvicultural practices that were effective elsewhere on sites for which they are ill-suited, sometimes resulting in useful practices being discredited and discontinued (Ashton and Kelty 2018). The history of multi-aged management in North America provides examples of the consequences of using inappropriate terminology (Curtis 1998; O’Hara 2002; Smith 1972).

As silviculture has expanded to embrace new ideas and management objectives over recent decades, development of novel treatments and modification of existing treatments has expanded the silvicultural lexicon. In many cases these new treatments resemble and build upon classical silvicultural practices (Palik et al. 2020), sometimes with only nuanced differences, but frequently they differ in silviculturist intent and emphasis on a broader set of management objectives than traditional practices. Examples include the variable retention practices that have been introduced, in various forms, on many public and private lands (Gustafsson et al. 2012) and are characterized by the intentional retention of live and dead structures associated with mature forests in order to provide functional continuity into the post-harvest environment. Achieving widespread acceptance of these new terms in the professional and scientific silvicultural communities has understandably proven challenging. New approaches may be difficult to define and differentiate, creating confusion over their value.

Another real challenge with the adoption of new silvicultural practices, and one that is particularly applicable to large land management agencies, is in the reporting of actions undertaken. The digital databases used for reporting silvicultural activities, such as the Forest Service's FACTS database, typically utilize a finite set of predefined activity codes, and updating these codes rarely keeps pace with management and research developments. Hence, a gap may exist between available reporting options and possible silvicultural actions. How does one report a variable retention harvest, a free selection harvest, or a variable density thinning when available activity codes do not include these terms? Such reporting challenges can create very real barriers to implementing complex treatments that do not neatly conform to classical silvicultural terminology. This may be a deterrent to applying some practices that may be useful in transformation to multi-aged structures and in long-term multi-aged management. Table 2.1 offers a crosswalk between terminology used in this guide and reporting codes available in the Forest Service's FACTS database (with notes below the table providing additional definitions of terms introduced in the table). Table 2.1 is one interpretation of a crosswalk, and others are possible. Moreover, as silvicultural treatments that may differ in intent or emphasis may have similar ecological effects, especially over short posttreatment timeframes, we recommend using the notes section of FACTS to supplement the numerical codes with brief written descriptions.

Table 2.1—A crosswalk between common silvicultural terminology used in this guide and reporting codes available in the Forest Service FACTS reporting database. Sources: 1 – Deal 2018; 2 – Powell 2013; 3 - Raymond et al. 2009; 4 - Beese et al. 2019; 5 – O’Hara et al. 2012; 6 - Palik and D’Amato 2023; 7 – developed from Churchill et al. 2016; 8 – Hood et al. 2022a; 9 – Keyes, C. pers. Communication, 10 - Society for Ecological Restoration 2004; 11 - Hood et al. 2022b; 12 – Miller et al. 2007.

Term	Definition	FACTS database options
Single-tree selection harvest	A regeneration method used to regenerate or maintain a multi-aged structure in which individual trees of all size classes are removed more or less uniformly throughout the stand to promote growth of remaining trees and to provide space for regeneration. ¹	Single-tree selection cut: 4151
Group selection harvest	A regeneration method used to regenerate or maintain a multi-aged structure in which trees of all size classes are removed and new age classes are established in small groups. ¹ Group sizes and shapes may vary, but are typically no more than twice the height of surrounding mature trees ¹ , up to a maximum size of 2 ac (0.8 ha). ²	Group selection cut: 4152
Shelterwood harvest	An even-aged regeneration method in which most trees are cut, leaving those needed to produce enough shade to produce a new age class in a moderated microenvironment. The sequence of treatments can include three cuttings: (a) an optional preparatory cut, (b) an establishment cut and (c) a removal cut. Harvesting can be uniform throughout the stand, in groups, or in strips ¹ .	Traditional shelterwood preparatory / establishment / removal cut: 4121 / 4131 / 4141
Irregular shelterwood harvest (or shelterwood with reserves or shelterwood with leave trees)	A multi-aged regeneration method based on the traditional shelterwood, but where some overstory cover is retained for more than 20 percent of the rotation length, and potentially for the entire rotation. Various types of irregular shelterwood harvest have been described ³ . Resultant stand structures may be uniform or grouped.	Shelterwood establishment cut with leave trees / Shelterwood removal cut with leave trees / Two-aged shelterwood establishment and removal cut (with / without reserves) / Two-aged shelterwood establishment cut (with / without reserves) / Shelterwood final removal cut (with / without reserves): 4131 / 4145 / 4193 / 4194 / 4196

Table 2.1 continued

Term	Definition	FACTS database options
Free selection system	A silvicultural system that integrates elements of both even- and uneven-aged management to develop and maintain the desired forest conditions. Emphasizes the diversity of stand structural components and spatial arrangements that exist at stand to landscape scales under natural disturbance regimes. Free selection uses continuous cover regeneration harvests (i.e., a regeneration harvest that retains some degree of mature overstory during harvest), as well as various intermediate treatments over multiple entries to manage for ecological objectives. Articulating management objectives and desired future conditions in a free selection system embraces qualitative description.	Potential to use many combinations of FACTS codes across the operational area (stand to sub-watershed to landscape). We suggest that managers divide operational area into stands or smaller units and assign best fitting FACTS codes where possible. E.g., sub-stand 1 – Group Selection; sub-stand 2 – Commercial Thin; sub-stand 3 – Improvement Cut. Where a stand cannot be subdivided (because within-stand patches are too small to be operationally distinct) we suggest using the code that best represents the greatest acreage. In FACTS notes, tag the entire free selection area together for future reference.
Variable retention harvest (VRH)	VRH has been considered as both a harvest method, and a silvicultural system that utilizes variable retention harvests as the primary regeneration harvest method. As a harvest method, regeneration is achieved using a structural retention harvest that preserves a proportion of live overstory trees (and (typically) snags and other structural components from the preceding stand) for at least one subsequent rotation, and in which at least 50 percent of the cutblock retains some mature forest influence (i.e., is within one mature tree height of a retained tree or the surrounding forest. ⁴⁾ In VRH, retained trees serve broader ecological purposes than seed and shelter, and this influences the selection of retained structures. As VRH retains some level of mature overstory during harvest, the VRH silvicultural system is multi-aged.	Where the long-term goal is a two-aged stand, the closest approximation may be the FACTS Two-aged stand clearcut with reserves (code 4177). Where the long-term goal is an uneven-aged stand (i.e., through repeated retention harvests), the FACTS Group selection cut (code 4152) may be the closest (but imperfect) approximation. If a strong motivation for treatment is improving wildlife habitat, then FACTS Wildlife Habitat Regeneration cut (code 6104) may be used, but is also imprecise.

Table 2.1 continued

Term	Definition	FACTS database options
Variable density thinning (VDT)	The term VDT has been used in several contexts over recent decades. Below we provide both the definition for the original reference to VDT (the “legacy” definition), as well as the practice that is now most commonly associated with the term “VDT”. Legacy definition: a tending method to increase stand structural heterogeneity, where spacing is deliberately varied throughout the stand or at designated features.⁵ New definition: A multi-aged regeneration method emphasizing the development of structural diversity. VDT treatments are characterized by the simultaneous application of gap creation, preserving unharvested areas (“skips”), and thinning in the matrix between gaps and skips. VDT treatments have most typically been implemented in homogeneous, relatively young second-growth stands.⁶	If structural diversification is the primary objective of treatment (i.e., the legacy definition), then free thinning, which is included in FACTS Commercial thin (code 4220) is most appropriate. Code 4521 - Precommercial thinning - is appropriate when implementing VDT in young stands that are below size thresholds for merchantability.” If establishing a new cohort is a co-objective of treatment, alongside structural diversification (i.e., the new definition), the closest approximation may be FACTS Group selection cut (code 4152).
ICO (“Individuals, Clumps, and Openings”)	An approach for marking, quantifying, and monitoring spatial structure that is based on numbers of trees, rather than basal area, and the proportion of trees that occur as individuals (“Individuals”), in tree clumps of different sizes (“Clumps”) and of open space in the stand (“Openings”). ICO application uses reference spatial structure found in frequent-fire forests with an intact disturbance regime.⁷ See box 6.2 in this guide.	ICO implementation should be viewed as a way of selecting which trees to cut and which to remove (i.e., marking). If ICO marking is used as a one-off intermediate treatment (as with a restoration treatment), the most suitable FACTS code may be the Improvement cut (code 4210). If intended for use in marking trees within a regeneration harvest context, a group selection harvest (code 4152) may be appropriate for an uneven-aged context, or one of the two-storied shelterwood codes for a two-aged structure.

Table 2.1 continued

Term	Definition	FACTS database options
Fuel reduction treatment	A treatment designed to alter live and dead aerial and/or surface fuels to moderate potential fire behavior and effects through the depletion or structural modification of fuel loads. ^{8, 9}	If mechanical, use FACTS Thinning of hazardous fuels / Fuel break: 1160 / 1180. If prescribed burning, use FACTS Broadcast burning / Under burn: 1111 / 1113. There is increasing evidence of the effectiveness of combining thinning and prescribed burning for fuel reduction. In such cases, it is recommended to report both activities in succession. For example, prescribed burning is often implemented after thinning to reduce activity fuels, so this would be recorded as one entry of code 1160 / 1180, and another of code 1111 / 1113.
Restoration treatment	A treatment designed to assist the recovery of an ecosystem that has been damaged, degraded, or destroyed ¹⁰ , typically toward a reference condition developed from a historic baseline or a historic baseline that has been adapted to promote greater resilience to future environmental conditions.	Most restoration treatments (absenting any consideration of regeneration requirements) should be viewed as intermediate treatments. The FACTS Improvement cut (code 4210) makes most sense for these treatments. If recruitment of a new cohort is an intended co-objective of treatment implementation, then one of the codes used for the irregular shelterwood or FACTS Group selection cut (code 4152) makes most sense. If restoration and regeneration objectives are being accomplished solely using prescribed fire, FACTS Natural regeneration – prescribed fire (code 7050) is appropriate.
Radial thinning	Radial thinning (or crop tree release, daylighting) is an intermediate treatment that is implemented with the goal of increasing the vigor and resilience of selected trees by localized removal of competing vegetation that is immediately adjacent to target individuals to increase available growing space for the latter ^{11,12} . Crop tree release has been widely implemented to increase commercial values of selected trees, while the term “radial thinning” has more recently gained traction in treatments designed to maintain or increase vigor in ecologically and/or culturally valuable older trees.	Commercial thin (FACTS code 4220) or precommercial thin (code 4521) will be relevant in almost all radial thinning applications, but combining this code with other intermediate treatments, especially improvement cut (code 4210), liberation cut (code 4211) and fuel reduction (codes 1160 , 1111 / 1113) may also be useful where variability in vegetation structure at sub-stand scales calls for simultaneous application of several intermediate treatments in different parts of the stand, or sequenced application of different treatments in the same areas of the stand.

Definitions for terms introduced in table 2.1 (Deal 2018)

Improvement cut: the removal of less desirable trees of any species in a stand of poles or larger trees, primarily to improve composition and quality

Liberation cut: a release treatment made in a stand not past the sapling stage to free the favored trees from competition with older, overtopping trees.

Patch cut: a variant of all regeneration methods in which small within-stand areas (patches) are regenerated, leaving the surrounding matrix unregenerated.

Selective cutting: a partial cutting, which generally is not a proper silvicultural method, consisting of removing only the most valuable trees, degrading the stand in the process.

Chapter 3: A Transformation Framework

Although silvicultural transformation benefits from a guiding plan, it also requires a willingness to deviate from this plan if the circumstances demand it.

The transformation from even-aged to multi-aged structure can be seen as a stepwise process beginning with information gathering and decision-making and ending in silvicultural treatments that accomplish the change in structure. There is much in common between planning a transformation and the process of developing a conventional silvicultural prescription. This includes the information sources used in formulating a transformation strategy, such as stand examination data. Also, in common with a silvicultural prescription, successful transformation will benefit from thorough documentation of the long-term structural goal, planned treatment sequence, and the underlying rationale for these choices. In many cases, transformation will require decades to accomplish, and these records of management intent will help ensure continuity through changes in personnel and information reporting systems.

Although silvicultural transformation benefits from a guiding plan, it also requires a willingness to deviate from this plan if the circumstances demand it. Transformation to complex structures, such as true all-aged stands, involves more uncertainty than transformation to simpler structures, such as two-aged stands (O'Hara 2001, 2014). A planned sequence of transformation treatments is important, but in all cases, managing uncertainty requires monitoring stand structure during the transformation process and responding accordingly. Equally necessary is flexibility to deviate from the planned sequence of treatments if monitoring reveals unexpected departure from the desired direction of stand development. This approach is essentially that of adaptive management (Minkova and Arnold 2020; Walters and Holling 1990). Applying this adaptive management mentality is even more appropriate given that transformations initiated over the coming decades will occur in a changing climate in the northern Rocky Mountains, the ecological consequences of which are far from certain (Halofsky et al. 2018). Ongoing monitoring can uncover unexpected changes in structure and/or composition and inform management responses to maintain stands on a trajectory toward the range of desired future conditions.

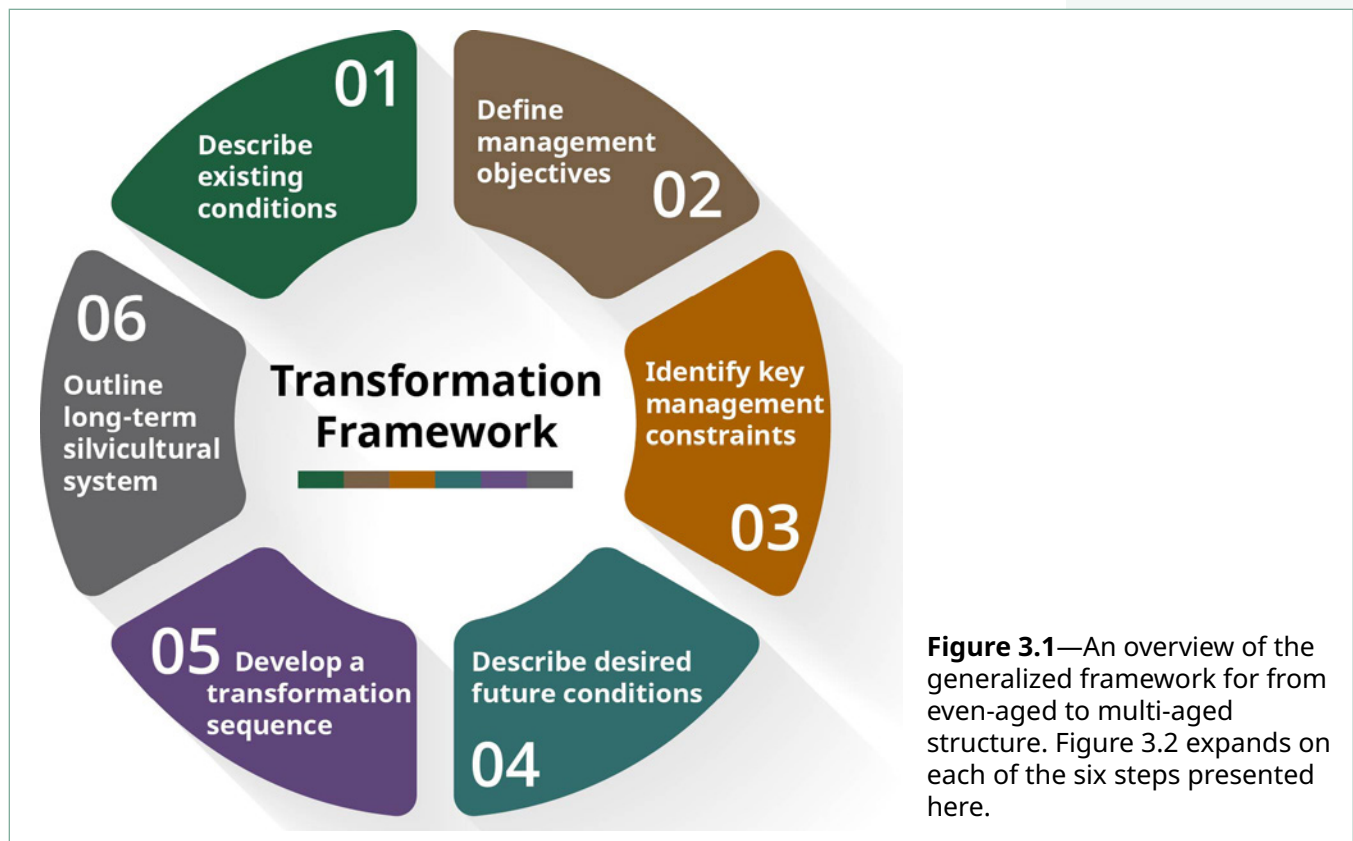
As with a traditional even-aged or uneven-aged system, transformation can be an intensive process with frequent entries to create cohorts and manage structure, or it can be less intensive. An intensive transformation approach might involve frequent silvicultural interventions to maintain stands on the planned trajectory. A less intensive transformation strategy may include, for example, (1) accepting longer timeframes for achieving standard regeneration densities following gap creation, (2) tolerating lower

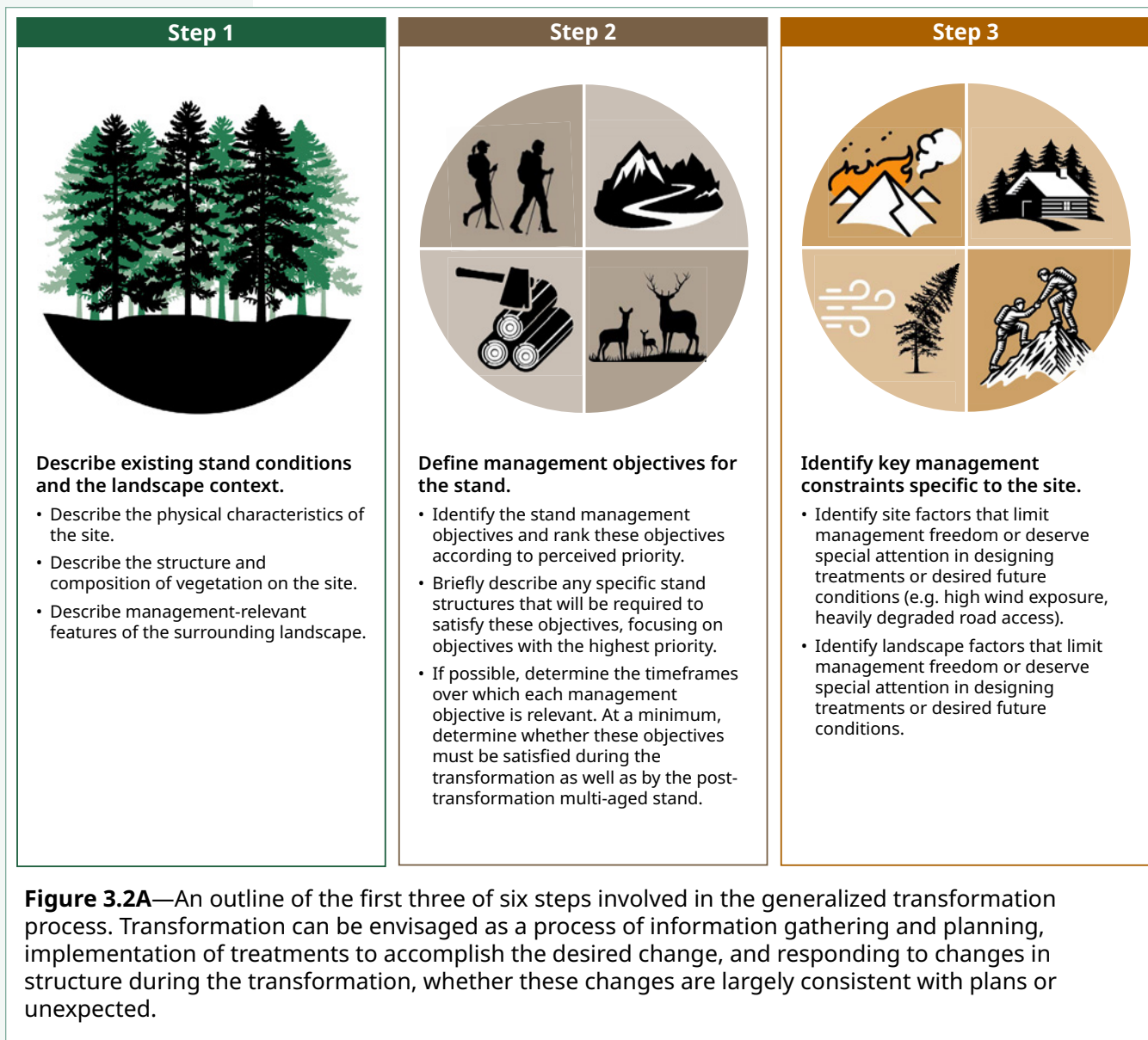
and more variable stand densities, or (3) slower seedling growth rates.

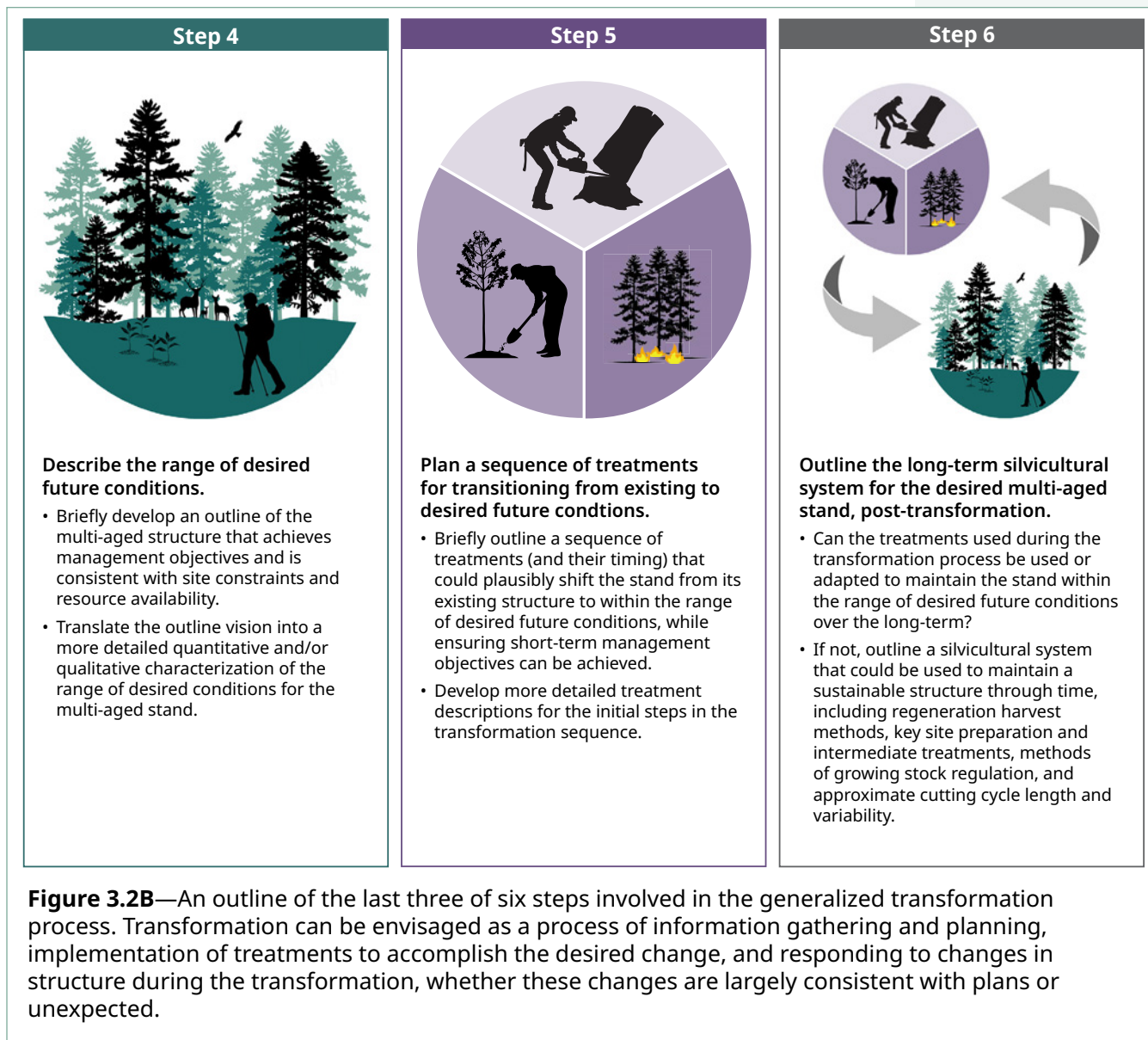
Therefore, transformation is a flexible process. Managers following a less-intensive transformation strategy may prefer to seek exemption from reforestation rules or emphasize treatment objectives other than new cohort regeneration when documenting and reporting the treatment in FACTS, simply because the current system is not tailored to complex forests.

Stepwise Transformation Framework

Figures 3.1 and 3.2 depict a generalized framework to guide practitioners through the transformation process. While the details of each step in this process will differ from case to case, the approach set out here is applicable in most situations. The primary focus of the remainder of this guide is on Steps, 1, 4, 5, and 6, as the definition of management objectives is typically not within a silviculturist's control, and identification of management constraints (e.g., steep slopes, lack of road network, dense herb or shrub layers) is highly site-specific. Many of the treatment options that may have use in silvicultural transformation, discussed in chapter 6, will also be relevant when developing a silvicultural system for the stand after transformation to the desired structure.







The Transformation Sequence

The transformation sequence is the series of treatments that shifts the target stand from the existing condition to within the range of desired future conditions. This treatment pathway is the most obvious component of a silvicultural transformation, although as figure 3.2 indicates, the transformation process should encompass far more than just the treatments themselves. Chapter 6 describes many of the treatment options that will be central to transformation in ponderosa pine stands.

Many factors will influence the treatments that make sense in any given transformation scenario, and the timing and sequence in which they are applied (fig. 3.2). An important example of this is the role of existing species (and their silvics) in developing the

Many factors will influence the treatments that make sense in any given transformation scenario, and the timing and sequence in which they are applied during the transformation.

initial steps in the transformation from an even-aged to a multi-aged structure.

For example, on a site in the *Pinus ponderosa* habitat type series, where ponderosa pine is the only overstory tree species, conducting a regeneration harvest may be a logical first step in the transformation to a multi-aged structure. After such a harvest, the site may not have the mineral soil that is the preferred seedbed for new seedlings, but the seedlings won't face competition from other species. The same is not true on many sites in the *Pseudotsuga menziesii* and *Abies grandis* habitat type series, where ponderosa is often accompanied by more shade-tolerant associates. Under these conditions, that same regeneration harvest may have undesirable consequences for ponderosa pine seedlings due to the greater competitiveness of associated tree species under the partial shade of the forest floor (Fajardo et al. 2006; Hood et al. 2020). Instead, intermediate treatments such as improvement cutting and prescribed burns may be required as preliminary steps to create the conditions for an effective regeneration harvest.

Existing stand conditions shape the initial steps of the transformation sequence, the desired future condition determines the ultimate end point, and management objectives may influence the choice of steps during the transformation. Conventionally, management objectives should not drive silvicultural prescriptions (i.e., the method) because management objectives flow from a desired stand structure and composition (i.e., the end goal), and many different treatment paths can produce a given structure. However, the period over which the management objectives are to be accomplished could influence the transformation sequence. As in other silvicultural contexts, different treatment pathways—for example, more intensive versus less intensive—may achieve a similar desired future condition but do so over very different time periods.

The range of forces that may influence the transformation sequence and the exploratory nature of transformation to multi-aged structure may initially be daunting, but practitioners can gain much insight from their prior experience on the ground and developing silvicultural prescriptions. There is more uncertainty and potentially more complexity involved in silvicultural transformation than continuing the existing management regime, but there is also much that is familiar. This guide and other information sources can be used to fill knowledge gaps, and monitoring and flexibility (described above) during the transformation process can help adjust to the inevitable uncertainty and unexpected occurrences associated with transformation.

Box 3 provides a set of questions that may help in planning the initial transformation steps. Chapter 7 provides hypothetical examples of transformations that could be implemented from a variety of existing conditions. The case studies in chapter 8 are working examples of the initial transformation treatments that have been implemented in ponderosa pine forests in the northern Rocky Mountains, with notes on lessons learned during the process.

Box 3: A few prompts for identifying the initial steps in the transformation sequence

Is a younger cohort of a shade-tolerant species currently present? That is, are shade-tolerant trees distributed across 5 percent or more of the stand area in sufficient density that survival of 5 or more trees per acre to reproductive maturity is probable without management intervention?

- **IF SO**, using intermediate treatments (prescribed fire, mechanical treatments) to remove or reduce existing understory tree density may be required before regeneration harvest.
- **IF NOT**, regeneration harvest may be a logical first step in the transformation sequence, provided other constraints are overcome. (For example, healthy, cone-bearing ponderosa pine are widely distributed in the overstory if planting will not be used.)

Does the existing overstory contain shade-tolerant tree species that are not dominant in the desired future condition?

- **IF SO**, improvement cutting may be required before, or at the same time as, the initial regeneration harvest, except where regeneration harvest can successfully target removal of shade-tolerant overstory species.
- **IF NOT**, regeneration harvest may be a logical first step in the transformation sequence, provided other constraints are overcome.

Is the existing overstory density moderate or high relative to potential site occupancy?

- **IF SO**, thinning will likely be required before single-tree selection type treatments can generate canopy gaps of sufficient size for competitive ponderosa pine regeneration.
- **IF NOT**, regeneration harvests targeting individual tree removal may successfully regenerate ponderosa pine.

Is the existing overstory density moderate or high, relative to potential site occupancy, and do trees have low, live crown ratios?

- **IF SO**, progressively reducing stand density will likely be required to build windfirmness, unless the site is extremely sheltered.
- **IF NOT**, considerable flexibility likely exists over residual stand density after the initial overstory treatment, unless the site is extremely exposed to wind.

Do existing overstory trees of desirable species display differences in crown structure and position (or vigor)?

- **IF SO**, vigorous trees in dominant canopy positions can be used as anchors around which to begin developing the desired spatial configuration for the stand.
- **IF NOT**, other factors (e.g., harvest layout practicalities, microsite conditions likely to inhibit or facilitate post-harvest regeneration) can determine how the desired spatial configuration is mapped onto the existing stand during the first overstory harvest.

Chapter 4: Existing Conditions

Describing Existing Stand Conditions

Accurate, up-to-date information on existing stand structure and composition is extremely valuable when planning a transformation from even-aged to multi-aged structure. This information will help address the following important questions:

1. Is the future condition that we might desire for this site actually feasible over a management-relevant timeframe given the current stand structure? The existing structure and composition of the stand is a major determinant of the possible structures and compositions that can realistically be developed, given site conditions, within an acceptable timeframe for accomplishing the transformation (this timeframe may itself be worth explicit consideration).
2. Can we plausibly satisfy the stated management objectives for this stand and site over the short- or long-term through silvicultural transformation? The existing condition of the stand provides a commonsense check on the reasonableness of management objectives during and after transformation.
3. How do we begin converting the stand to the desired future condition? The existing conditions directly inform the development of an appropriate sequence of treatments for achieving the desired multi-aged structure. This is especially true for the first few steps in the transformation process.

Knowledge of existing site and stand conditions informs the transformation to multi-aged structure in the same way that stand examination data informs the development of conventional silvicultural prescriptions. And as is the case when developing any silvicultural prescription, a basic understanding of the site's biophysical characteristics—such as elevation, climate, soil types, habitat type—is also necessary for designing a sequence of treatments for the transformation.

In addition to this information on site characteristics, a description of existing stand structure is critical (fig. 4.1). This description should include density-based metrics for trees in all canopy layers (including seedlings and saplings), tree heights, and crown characteristics. These metrics can be obtained from a smaller sample of trees due to the intensive nature of such

measurements. Descriptions should also encompass dead wood (for example, number and/or total volume of down logs, number of small and large snags per acre in sound and rotten condition) and both the vertical (for example, canopy stratification) and horizontal structure (for example, size of existing openings) of the stand. Other noteworthy structural attributes, such as evidence of past disturbances and notable wildlife use of the stand, can also be included in the description of existing conditions if they help inform the development of the transformation sequence.

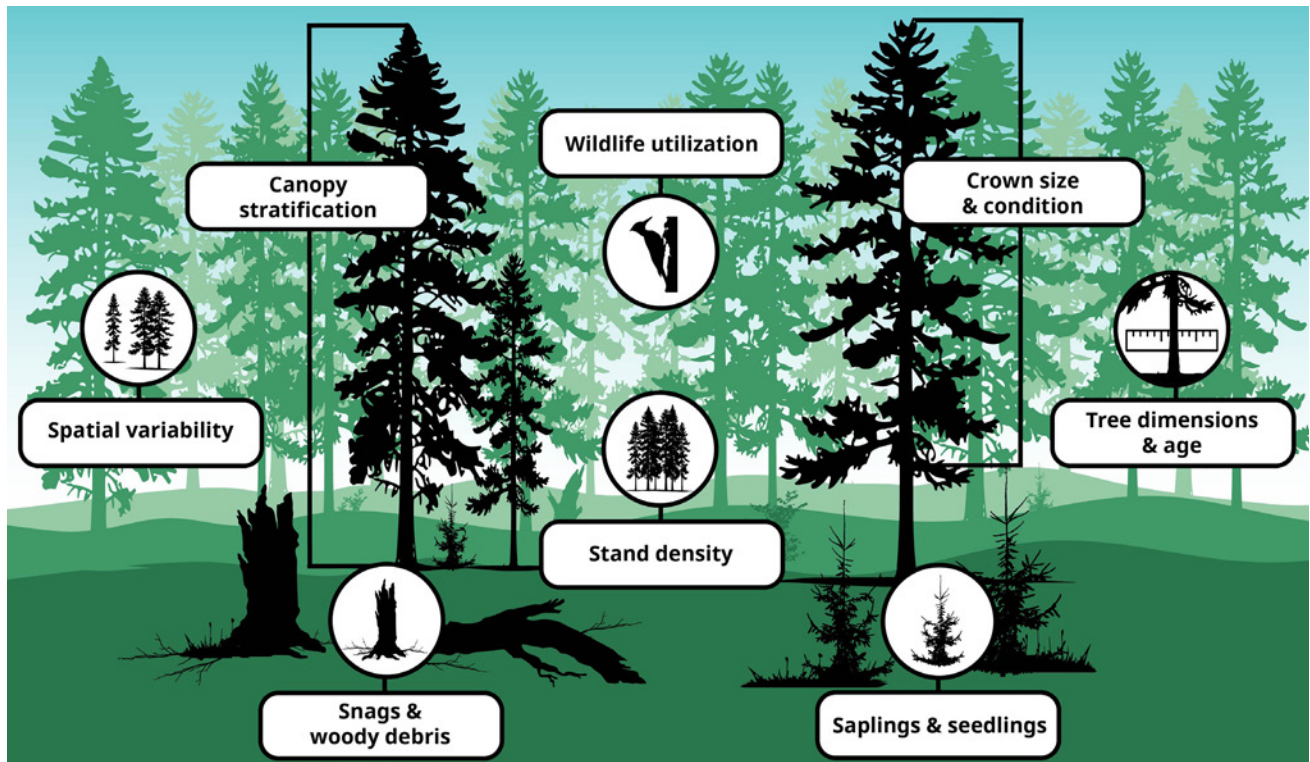


Figure 4.1—An illustration of the different structural elements and features of the stand that may be included in the description of existing stand conditions. The level of detail to supply for each of these structural elements should suit the requirements of the transformation and those implementing it.

The level of detail and precise blend of information used to describe existing stand conditions will vary according to context and user preference. Similarly, different formats may be used for documenting existing stand conditions. Some silviculturists may find a detailed quantitative description of stand conditions most useful, while others will favor a balance of qualitative and quantitative information. In some situations, visual depictions of existing stand structure may be a useful way of identifying potential transformation options. These visual aids might include detailed photographs, NAIP imagery, simple hand-drawn or digital diagrams or cartoons, and outputs generated by the Stand Visualization System within the Forest Vegetation Simulator

(Dixon 2002), or forest visualization software such as the Visual Forester Stand Designer (Alpine Land Information Services 2020) application that is used throughout this management guide.

Relating the Stand to Its Landscape Context

Landscape context can have a bearing on stand-scale actions, and this should be reflected in the description of existing stand conditions where necessary. Silviculture provides the means of accomplishing changes in vegetation structure to meet resource objectives for the stand. Some of these objectives may in fact be determined by landscape context (e.g., North et al. 2019; Peery et al. 2017). For example, providing habitat for threatened wildlife species that are scarce on the landscape but found within the stand. This type of information should be incorporated into the management objectives that will be defined in step 2 of the *Transformation Framework* (see chapter 3, section 1 - Stepwise Transformation Framework) and generally requires no further elaboration in the description of existing conditions. In other cases, features of the surrounding landscape (or perhaps just the immediate vicinity of the stand—the *meso-scale*) influence silvicultural decision-making without being a direct management objective for the stand.

For example, consider an unburned site that is adjacent or near to a large, high-severity wildfire scar. A possible implication of this nearby wildfire scar is the preference for reserving a higher density of vigorous, mature trees in the unburned stand during the transformation sequence than would otherwise be required for the transformation or for achieving the stand management objectives. These reserved trees will be an important seed source for the burned area. Situations such as this, where landscape context could modify the transformation sequence or could factor into the desired future conditions, merit description alongside the existing conditions within the stand itself.

The description of relevant landscape or meso-scale factors need not be extensive and will not be required in all situations. Where relevant landscape factors do exist, the description could consist of an annotated map, aerial photograph, or a simple hand-drawn sketch or written explanation of the important factors. The aim is not to provide a detailed analysis, but enough information to help in planning the transformation sequence. Any additional detail that is required for designing individual silvicultural treatments will be provided when developing silvicultural prescriptions for these activities.

A Typology of Generalized Existing Conditions

Ponderosa pine stands in the northern Rocky Mountains exhibit a wide range of stand structures resulting from diverse site conditions and management histories. This includes structurally diverse, multi-storied uneven-aged and two-aged stands, as well as structurally homogeneous young plantations resulting from past clearcutting and planting. The focus in this guide is on stands that do not currently exhibit a sustainable multi-aged, ponderosa pine-dominated structure. This includes stands that meet textbook definitions of *even-aged*, as well as stands with a pine-dominated overstory that are: (1) currently transitioning *from* an even-aged structure to a two-aged structure as a result of infilling by shade-tolerant species in the understory; or (2) transitioning *toward* even-aged structure as a result of overstory mortality under the influence of intensifying resource competition with a dense, shade-tolerant understory (and the resultant reduction in overstory vigor).

From a silvicultural perspective, each stand is—and should be treated as—a unique case. From an instructional perspective, it can be useful to define generalized cases that represent the broader population of ponderosa pine stands. Therefore, the remainder of this chapter presents five generalized stand conditions (“existing condition types”) that research and inventory data indicate are present in northern Rocky Mountain landscapes (e.g., Fiedler 1996; Fiedler et al. 1999; O’Hara 1996). These existing condition types are not the only starting points for transformation to a multi-aged structure. Rather, they illustrate representative stand structures that might be the target of transformation. Most users of this guide will be able to identify similarities between one or more of these existing condition types and stands that are of management interest for silvicultural transformation.

For each of the existing condition types in this section, we provide visual depictions of the physical structure of a representative example stand, with accompanying quantitative summary data and a diameter distribution. Diameter distributions are a useful diagnostic tool for examining stand structure. There is a common—but misleading—perception that strict adherence to a target diameter distribution is fundamental to uneven-aged management. For this reason, box 4 provides an introduction to diameter distributions and their historic role in multi-aged management.

Box 4: Diameter distributions and multi-aged management

Diameter distributions provide a visual depiction of stand structure and are a valuable tool for monitoring changes in structure caused by tree regeneration, growth, senescence, and removal. The most common form of diameter distribution plots tree diameter or diameter class (x-axis) against trees per acre or per hectare (y-axis). Distributions may also be constructed using basal area or other metrics of stand density on the y-axis. In this guide we make extensive use of diameter distributions, such as the one below (fig. 4.2).

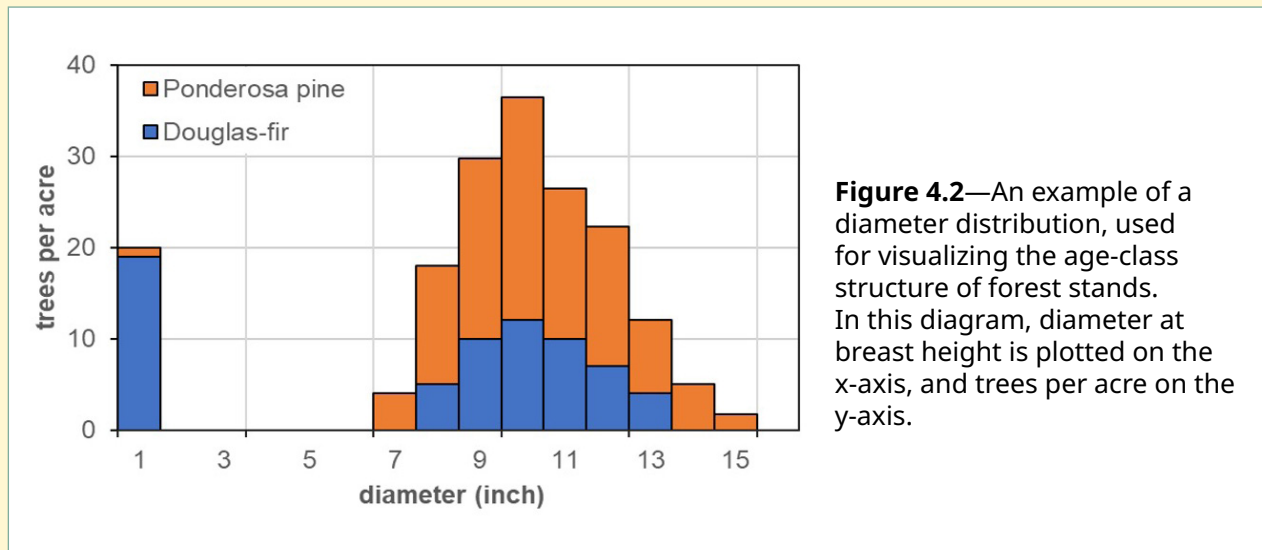


Figure 4.2—An example of a diameter distribution, used for visualizing the age-class structure of forest stands. In this diagram, diameter at breast height is plotted on the x-axis, and trees per acre on the y-axis.

Widely used in ecological research (e.g., Forrester et al. 2021; Lorimer and Frelich 1998; Shorohova et al. 2009), diameter distributions have also been used in silviculture research and practice for over a century (e.g., Arbogast 1957; de Liocourt 1898; Kerr 2014). In a practical context, diameter distributions can help in the design of target stand structures and in evaluating and tracking the effect of treatment through time. In this management guide, we use diameter distributions to visualize the age-class structure of stands before and after transformation to multi-aged structures and after silvicultural treatments.

Of particular use in this guide is the information that diameter distributions can reveal about the number of cohorts in the stand and their size and composition. Although stands with a given age-class structure may exhibit a wide range of diameter distributions depending on their species composition (and the silvics of those species), site characteristics, stand age, and disturbance history, there are some general trends that can be used as basic diagnostic aids. An important caveat is that while diameter distributions can be indicative of the absolute and relative ages of trees growing in the stand, the relationship between tree age and size is far from precise. Trees of a given age may grow at very different rates for many reasons. Likewise, two trees of the same size may be very different ages. Therefore, it is always a good idea to obtain a small sample of tree ages from across the size distribution within a stand using increment cores (approximate ages can often be counted in the field).

Notwithstanding these caveats, even-aged stands typically show some variation of a unimodal diameter distribution (fig. 4.3a) in which the peak represents a single cohort. This peak may be skewed to the left or right, based on species composition, site characteristics, and stand disturbance history. For instance, an even-aged, stratified mixture containing one dominant shade-intolerant species and a secondary shade-tolerant species (for example, grand fir growing beneath a western larch overstory) may display a left-skewed diameter distribution, such as that in figure 4.3b.

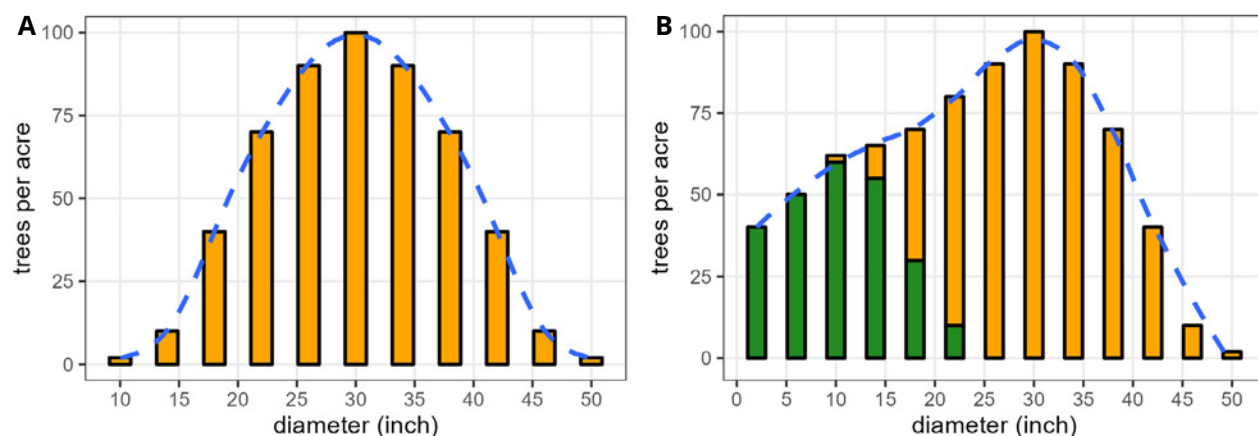


Figure 4.3—(a) The classic unimodal diameter distribution of an even-aged, single-species stand, and (b) an even-aged stand containing two species, one of which is shade-tolerant (green bars) and able to maintain slow growth in the partial shade of a less tolerant species (orange bars) that exhibits higher growth rates during stand establishment.

Two-aged stands, such as those produced by irregular shelterwood or variable retention harvest treatments or by a moderate-severity natural disturbance in an even-aged stand, are typically strongly bimodal, with peaks for each cohort (fig. 4.4a).

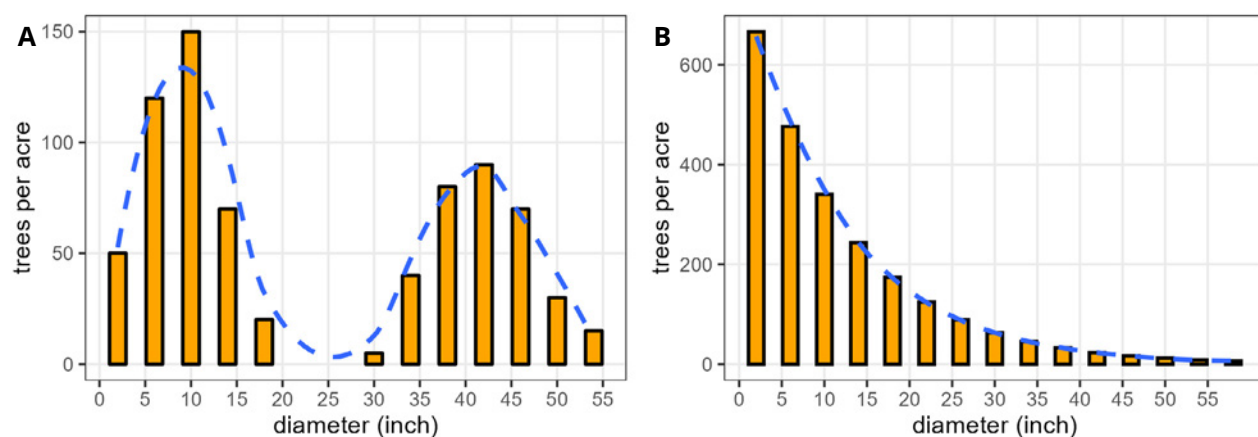


Figure 4.4—(a) The bimodal distribution of a two aged stand. The relative height of the peaks for the two cohorts is influenced by factors such as the amount of growing space created by harvest or mortality in the older cohort. (b) An approximately (but not perfectly) negative exponential diameter distribution from an uneven-aged stand containing four cohorts of the same species. This distribution loosely conforms to the “reverse-J” shape that is often ascribed to uneven-aged stands.

The shape of diameter distributions from uneven-aged stands may vary widely. The reverse-J-shaped curve (or negative exponential curve) is the textbook representation for unmanaged uneven-aged stands (fig. 4.4b). Although uneven-aged stands may indeed display distributions that approximate the reverse-J-shaped curve, a derivative known as the *rotated sigmoid* appears to be more common than a true negative exponential curve in unmanaged uneven-aged stands (e.g., Goodburn and Lorimer 1999; Leak 1964; Zenner 2005). The rotated sigmoid distribution resembles the reverse-J curve (fig. 4.5a), especially when plotted on axes with a standard scale (i.e., non-log transformed). However, it contains a higher proportion of the total stems (and stand volume) in the middle of the distribution than a true negative exponential curve because of lower mortality rates among these mid-size stems. These reduced mortality rates create a plateau in the middle of the distribution that is best visualized by plotting the diameter distribution on semi-logarithmic axes (a graph where the y-axis is scaled on the logarithm) (fig. 4.5b).

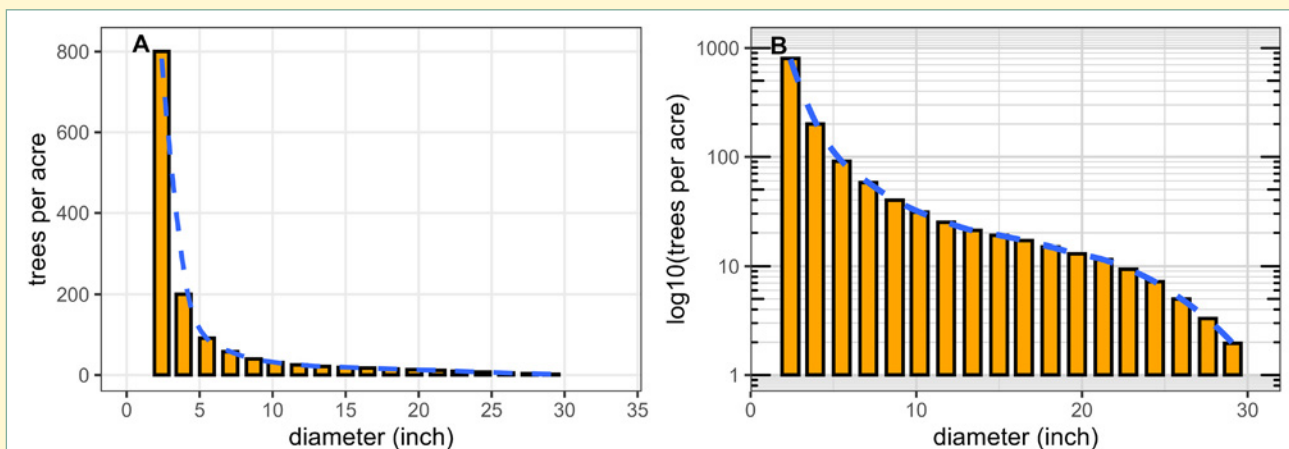


Figure 4.5—A classic rotated sigmoid diameter distribution. Compared to a classic negative exponential reverse-J distribution, the rotated sigmoid contains more stems in the middle of the distribution. This can be hard to detect when plotted on normal scales (A), but is clear when plotted on a semi-logarithmic graph in which the y-axis is scaled to $\log_{10}$ (B). When plotted on this semi-logarithmic graph, a classic negative exponential curve will become a diagonally-sloping straight line without the “S” shape of the rotated sigmoid.

Unmanaged uneven-aged stands may also display diameter distributions that depart heavily from the reverse-J. For example, the uniform to near-unimodal distributions in figure 4.6 are from uneven-aged, old-growth ponderosa pine stands in western Montana, reconstructed as of the year 1900 (Arno et al. 2005).

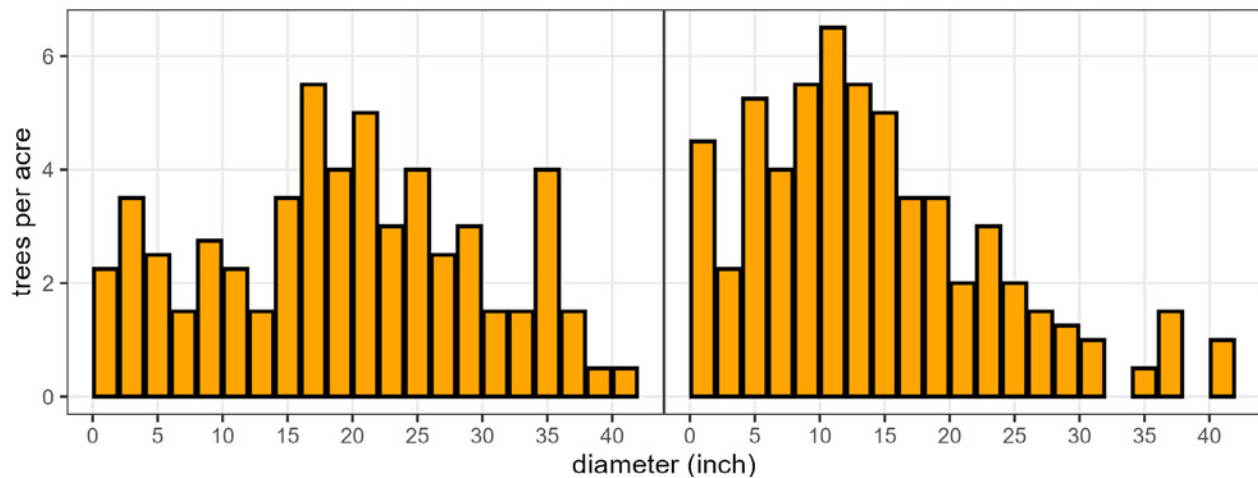


Figure 4.6—The diameter distributions for two old-growth ponderosa pine stands in western Montana, reconstructed as of the year 1900. Both stands have experienced repeated low-severity fires and contain many cohorts. Adapted from Arno et al. (1995).

Why dwell on the diameter distributions of unmanaged, uneven-aged stands? These templates from *natural* forests that were assumed to be in equilibrium—unchanging through time—formed a basis for many of the historical stocking control concepts developed for managed, balanced uneven-aged stands. Specifically, the assumptions that (1) natural uneven-aged stands display a negative exponential reverse-J diameter distribution and that (2) this distribution is sustainable through time, underpins the BDq method of stocking control for selection-based management systems in balanced stands (e.g., Arbogast 1957; Meyer 1943; O'Hara 2014). Similarly, the rotated sigmoid form is central to the plenter system—an intensive form of single-tree selection practiced in the silver fir (*Abies alba*)–Norway spruce (*Picea abies*)–European beech (*Fagus sylvatica*) forests of central and eastern Europe.

The BDq method is described further in chapter 6 of this management guide. In brief, its application involves development of a guiding reverse-J diameter distribution that is used to assess how many trees to retain in each diameter class across the cutting cycle. In this process, diameter classes are used as a surrogate for age (an assumption that is not without flaws, Seymour and Kenefic 1998) with the objective of producing a balanced distribution in which each cohort occupies the same amount of growing space. The guiding diameter distribution is negative exponential in shape, with the precise form determined by the q-factor, a ratio of the number of trees in a diameter class to the number of trees in the adjacent diameter class (fig. 4.7). Maintaining this target diameter distribution across harvest entries is proposed as a means of ensuring sustained timber yield through time at the stand scale (O'Hara 2014). During harvests, trees from diameter classes that are below the guiding curve (diameter classes that are in deficit) are retained, while trees in diameter classes above the guiding curve (diameter classes that are in excess) are cut down to the curve. Deficits may be compensated by retaining additional trees in adjacent classes that are in excess.

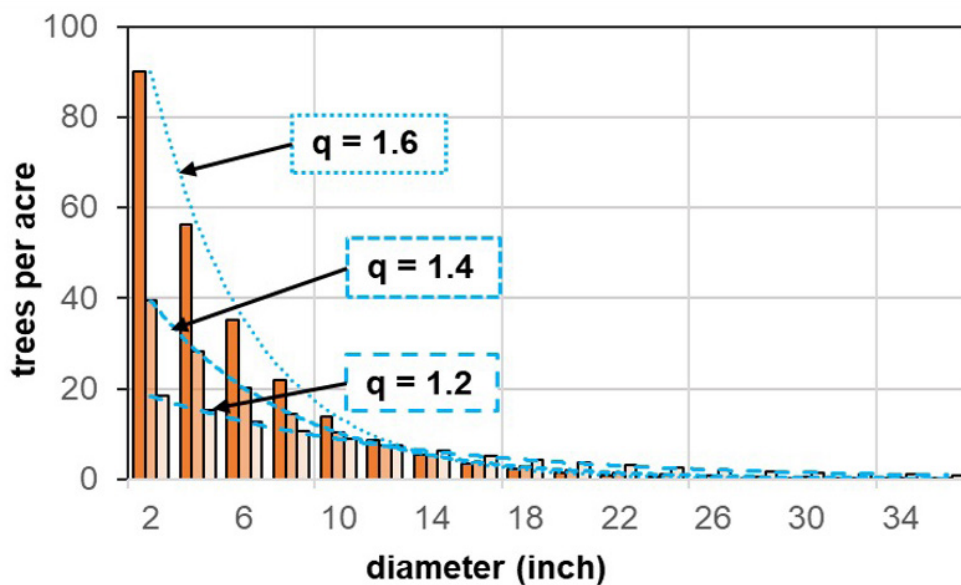


Figure 4.7—The bar chart above shows the effect of different q-factors on the shape of the classic reverse-J uneven-aged diameter distribution used as a target in the BDq method of stocking control. Three reverse-J diameter distributions are shown. These distributions have identical values of residual basal area (B) and maximum diameter (D), but q-factors ranging from 1.2 to 1.6. As this diagram illustrates, increasing the value of q results in a steeper curve, indicating more severe reductions in the number of stems from one diameter class to the diameter class above.

Using single-tree selection and BDq stocking control, the process of transforming an even-aged stand (unimodal diameter distribution) to an uneven-aged stand (negative exponential distribution) involves reducing the peak of the unimodal diameter distribution for size classes that are present in excess of the guide and adding new cohorts to the left of the distribution through successive selection harvests and pulses of regeneration. See figure 4.8 for a simplified example.

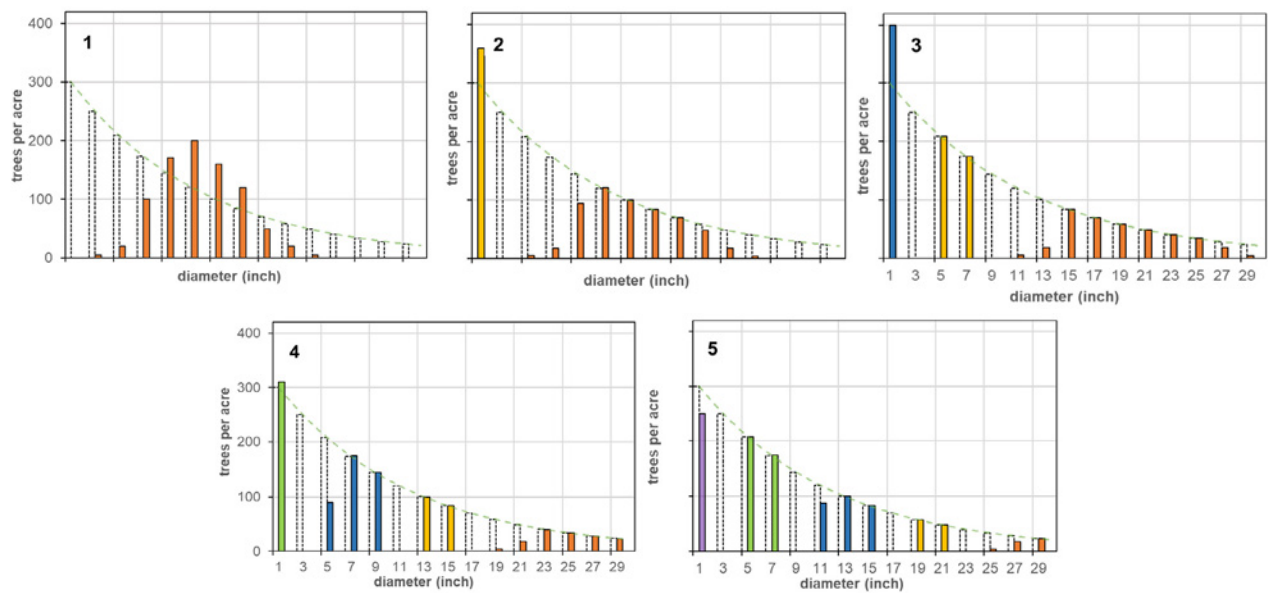


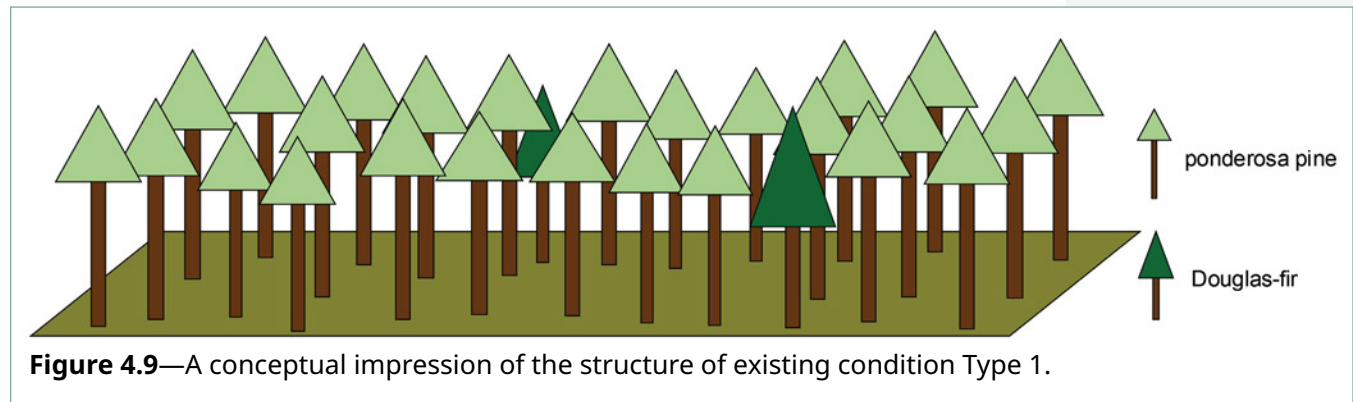
Figure 4.8—The progression of a diameter distribution from unimodal to negative exponential during the transformation from even-aged to uneven-aged structure using single-tree selection with the BDq method of stocking control and a q-factor of 1.2. The guiding diameter distribution for a q-factor of 1.2 is shown as a green dashed line. Beginning at time period 1, each numbered time-period shows the regeneration of a single cohort, depicted as a different color. Open dashed bars show the target height for each diameter class.

While diameter distributions, such as those used in the BDq and plenter systems, have value as precision stocking control tools, their use has tradeoffs. From a technical perspective, the assumptions that (1) the reverse-J and rotated sigmoid distributions are indeed sustainable through time, and (2) strict adherence to one of these discrete diameter distributions produces structural outcomes more consistent with natural uneven-aged stands, are questionable. Nor is such “naturalness” a necessary target in all management scenarios (Leak 1964; O’Hara et al. 2007; O’Hara 2014; Pond and Froese 2014; Seymour and Kenefic 1998).

At a practical level, these precision stocking control tools may be too rigid, complex, and resource intensive to implement in some circumstances (e.g., Guldin and Baker 2006; Powell 2018). In some regions—especially those in which even-aged management has become the norm—uneven-aged management is synonymous with stocking control using the BDq system. This notion can also be found in silvicultural texts (Nyland 2016). This creates the perceptions that multi-aged management must use diameter distributions as strict guiding targets during timber marking and harvesting, and that all forms of multi-aged management are inherently complex.

By using diameter distributions extensively in this guide, we hope to illustrate their use in a variety of situations. Chapter 6 shows a wide range of alternative, multi-aged stocking control methods of varying degrees of complexity, some of which use diameter distributions while others do not.

Existing condition Type 1: young, even-aged ponderosa pine stands—



Existing condition Type 1 is a young, even-aged, ponderosa pine-dominated stand. Stand density is high, with very little vertical or horizontal structural diversity. This condition may have been established as a plantation in the latter half of the twentieth century. A similar structure could be produced by a pulse of natural regeneration after a high-severity disturbance on a relatively productive site, although this would likely exhibit more variability in tree spacing and size. Intense inter-tree competition and competitive mortality occurs in stands of existing condition Type 1 due to the high stand density. As a result, such stands are extremely vulnerable to climate and disturbance stressors, such as drought, bark beetles, and wildfire.

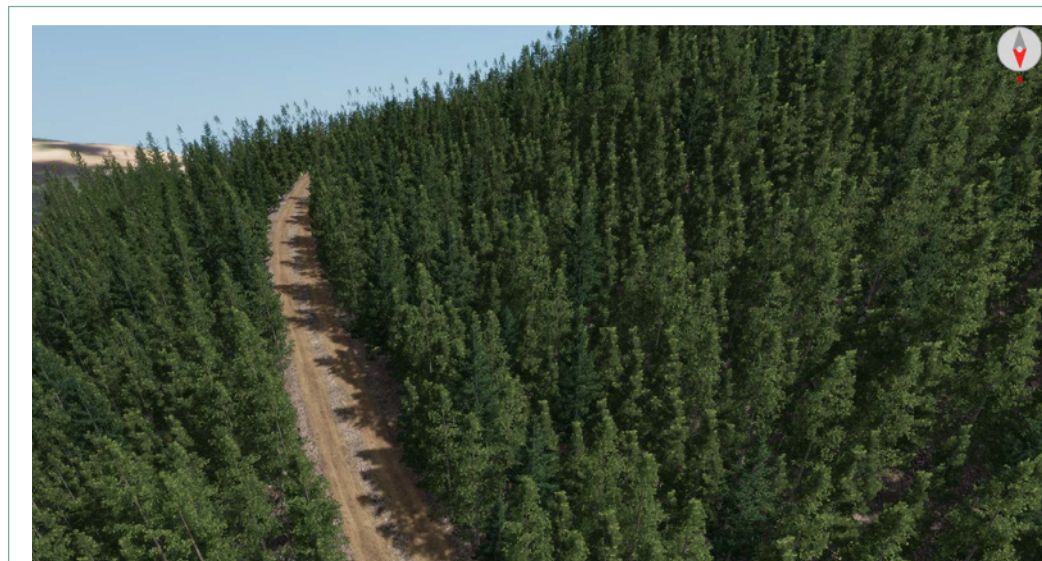




Figure 4.11—High stand density in existing condition Type 1 results in low light penetration to the forest floor and little to no available growing space, evident in this image of the understory of a computer-generated stand, taken from one of the rare locations where an image is not a wall of foliage.

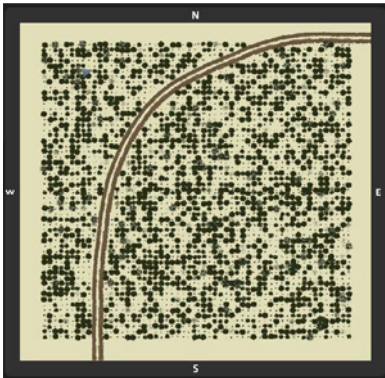
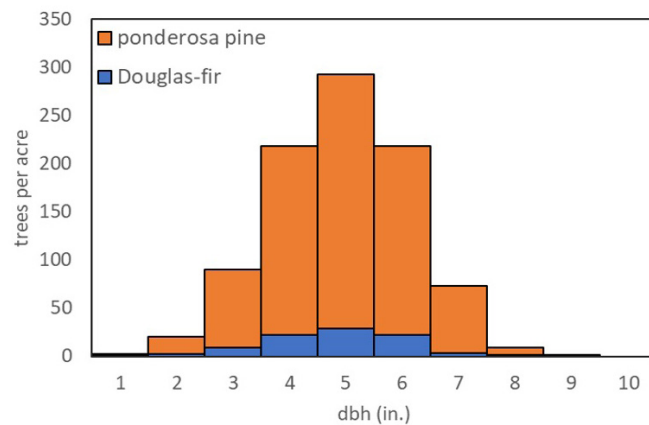


Figure 4.12—The homogeneous structure of existing condition Type 1 is evident in this planimetric view (taken overhead, looking down), which shows the high stand density and regular spacing of trees. Trees are represented by points, with larger points and heavier shading indicating larger trees.

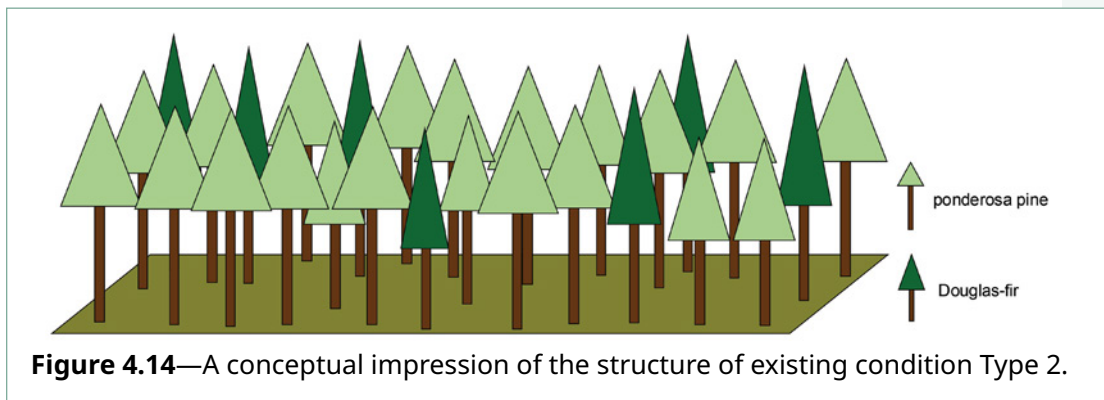
Figure 4.13—An example diameter distribution of existing condition Type 1 for a stand in the *Pseudotsuga menziesii* habitat type series.



Stand Summary	
Species	PIPO, PSME
Age (years)	40
Age structure	Even-aged
Stratification	Single-storied
QMD (in.)	5
Trees per acre	925
Basal area (ft ² ac ⁻¹)	130
SDI	306

Table 4.1—Example structural characteristics of existing condition Type 1 for a stand in the *Pseudotsuga menziesii* habitat type series. PIPO – ponderosa pine, PSME – Douglas-fir, QMD – quadratic mean diameter, SDI – stand density index. Statistics include stems ≥ 1 inch.

Existing condition Type 2: mid-successional, even-aged stand, low diversity—



Existing condition Type 2 is a mid-successional, even-aged stand with high overstory density and low structural diversity. The overstory is dominated by ponderosa pine, although some Douglas-fir is present on sites in the *Pseudotsuga menziesii* habitat type series. Crown differentiation is occurring due to inter-tree competition, gradually segregating the stand into trees in dominant, co-dominant, intermediate, and suppressed crown classes. Resource constraints lead to competitive mortality (self-thinning), creating relatively small-diameter snags and down woody debris. As with existing condition Type 1, stands in Type 2 are at risk from external stressors, including drought, insects, and wildfire. Many older, former plantations would fit into this condition type, as would stands regenerating naturally following high-severity fire.



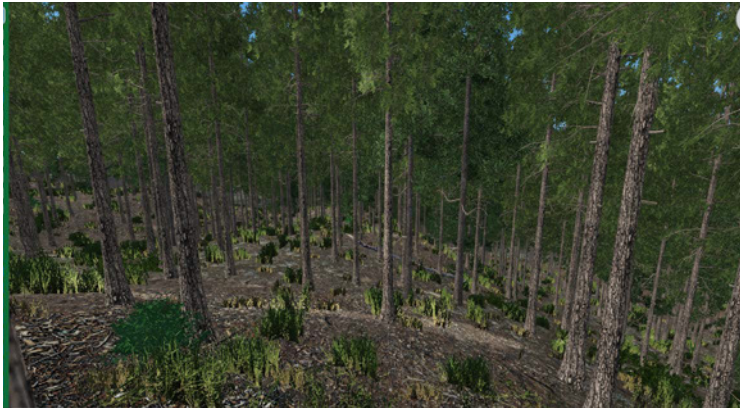


Figure 4.16—High stand density in existing condition Type 2, evident in this image, results in high canopy bulk density and aerial fuel continuity. These conditions increase the potential for crown fire spread and high mortality during fire events.

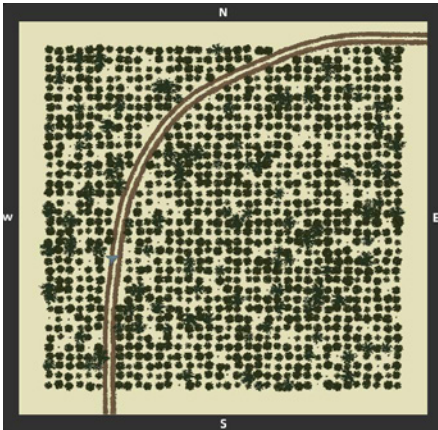
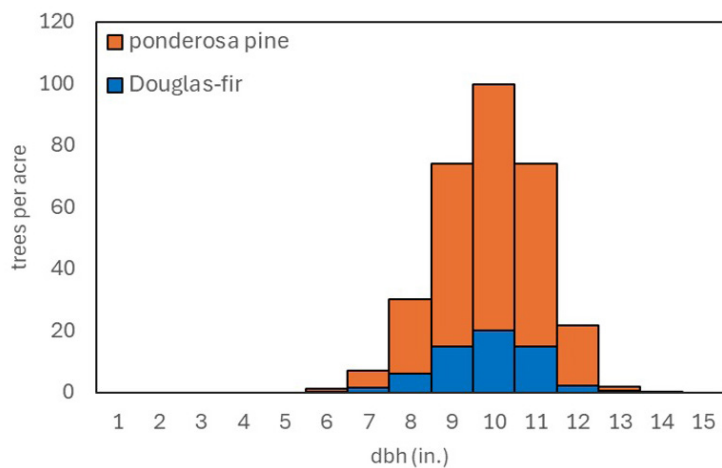


Figure 4.17—A planimetric view of existing condition Type 2 reveals a similarly regular spacing of trees to that of Type 1.

Figure 4.18—An example diameter distribution of existing condition Type 2 for a stand in the *Pseudotsuga menziesii* habitat type series.



Stand Summary	
Species	PIPO, PSME
Age (years)	80
Age structure	Even-aged
Stratification	Single-storied
QMD (in.)	10
Trees per acre	310
Basal area (ft ² ac ⁻¹)	167
SDI	306

Table 4.2—Example structural characteristics of existing condition Type 2 for a stand in the *Pseudotsuga menziesii* habitat type series. Acronyms follow notes to table 4.1.

Existing condition Type 3: early to mid-successional, transitional two-aged stand—

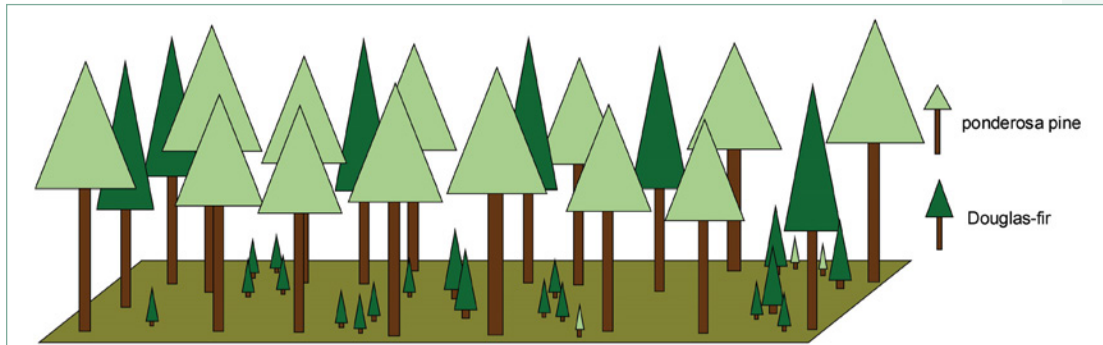


Figure 4.19—A conceptual impression of the structure of existing condition Type 3 in a mid-successional stand.

Existing condition Type 3 is characterized by the presence of a second cohort beneath an established overstory, beginning the transition to a two-aged stand. In the northern Rocky Mountains, existing condition Type 3 is most common in mid-successional stands with some vertical and horizontal diversity. In these stands, the modest light levels at the forest floor create conditions for understory reinitiation by shade-tolerant species (typically Douglas-fir or grand fir). A variation of existing condition Type 3 is also found in young stands, post canopy closure. In these younger stands, understory seedlings and saplings may be a second cohort but could also belong to the same cohort as the overstory i.e., a vertically-stratified, mixed-species even-aged stand. In both cases, the presence of a shade-tolerant understory signposts a future shift from ponderosa pine dominance in the absence of moderate-severity disturbance. Existing condition Type 3 may result from a variety of developmental pathways, including moderate density natural regeneration (potentially due site limitations) after a stand-replacing disturbance (including clearcutting), or natural seeding of shade tolerant species during early plantation establishment.

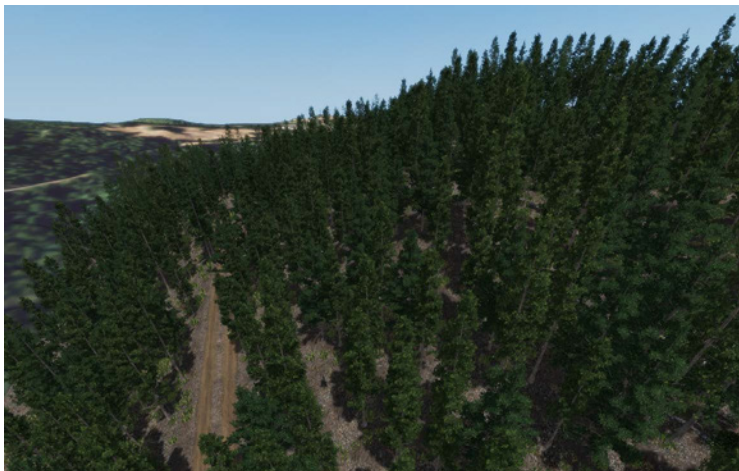


Figure 4.20—An aerial view of a mid-successional stand conforming to existing condition Type 3. Compared to Type 2, the overstory exhibits lower stand density and less regular tree-spacing, both clear in this image.



Figure 4.21—An image of the understory in a mid-successional stand conforming to existing condition Type 3. Patchy light conditions and the presence of small canopy gaps create conditions that are more favorable to Douglas-fir regeneration than ponderosa pine (on sites in the *Pseudotsuga menziesii* habitat type series). This regeneration begins the transition toward a two-aged structure.

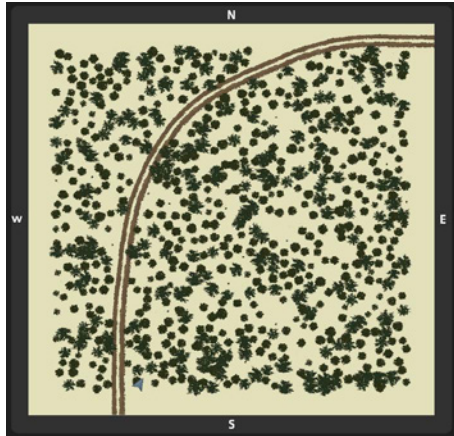
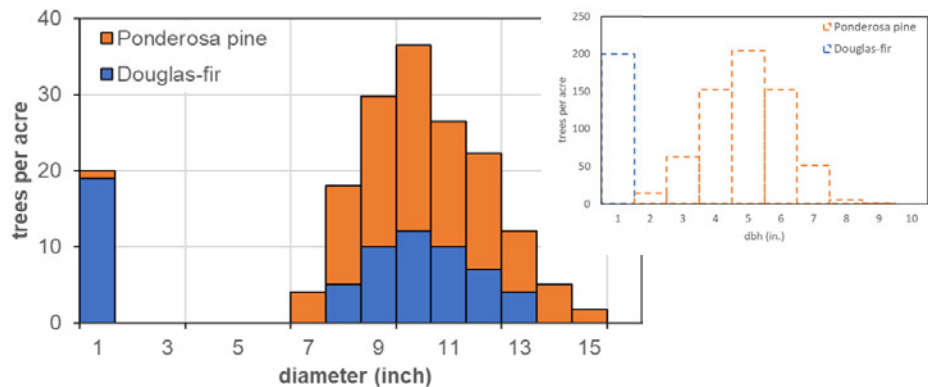


Figure 4.22—A planimetric view of a mid-successional stand conforming to existing condition Type 3. Small diameter understory regeneration is generally too small to appear in this figure.

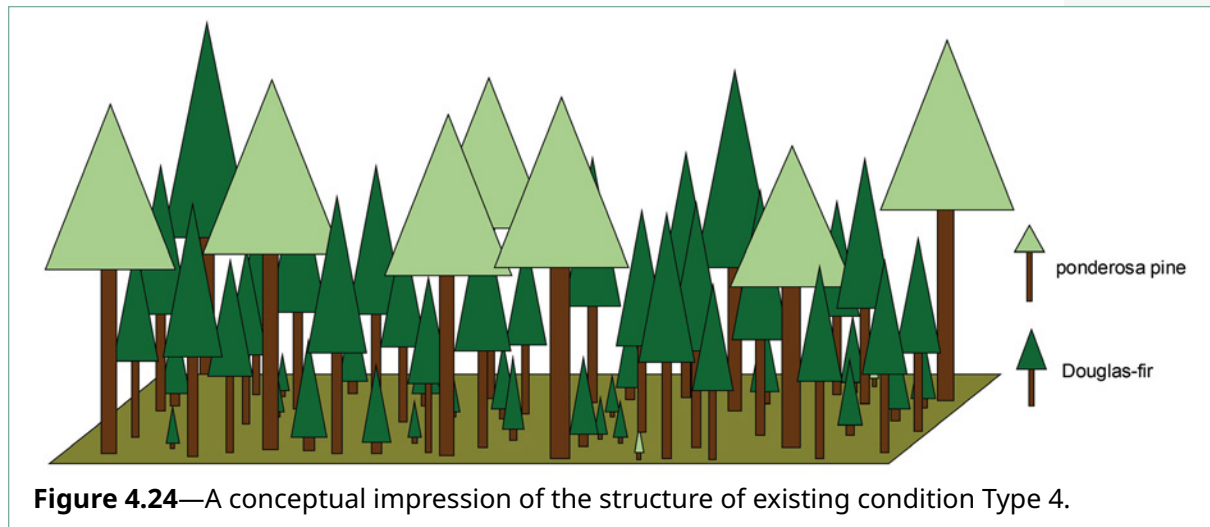
Figure 4.23—An example diameter distribution for a mid-successional stand conforming to existing condition Type 3 on a site in the *Pseudotsuga menziesii* habitat type series. The inset diameter distribution provides an example for an equivalent young stand in this existing condition Type.



Stand Summary	Young	Mid-successional
Species	PIPO, PSME	
Age structure	Transitional two-aged	
Stratification	Transitional two-storied	
Age (years)	40	80
QMD (in.)	4	10
Trees per acre	850	176
Basal area (ft ² ac ⁻¹)	92	102
SDI	220	168

Table 4.3—Example structural characteristics for young and mid-successional stands conforming to existing condition Type 3 for a site in the *Pseudotsuga menziesii* habitat type series. Acronyms follow notes to table 4.1.

Existing condition Type 4: mid-successional, two-aged stand—



Existing condition Type 4 is a mid-successional stand with an overstory aged approximately 100–120 years and an understory and midstory of seedlings, saplings and small trees. The overstory is predominantly ponderosa pine and has relatively low stem density. The lower canopy layers are Douglas-fir- or grand fir-dominated and are moderately to extremely dense. Basal area is relatively high, and resource competition is likely to suppress growth rates of trees in all canopy layers and increase mortality risks from insects and pathogens. This structure also presents high fire risk because of the abundant ladder fuels. Stands with this structure could result from heavy selection harvests in the past or by low-to-moderate severity natural disturbance followed by natural regeneration during mid- to late-twentieth century fire exclusion.



Figure 4.25—An aerial view of a stand conforming to existing condition Type 4, showing the high density of midstory and understory conifers.



Figure 4.26—A view of the understory in one of the denser patches of vegetation in existing condition Type 4. This image clearly shows dominance of Douglas-fir in the understory, which includes saplings and small trees of varying size. Here, understory and midstory conifers form a vertically-continuous fuel ladder connecting surface and canopy fuels.

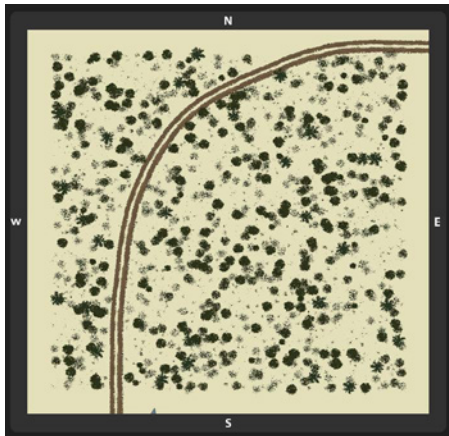
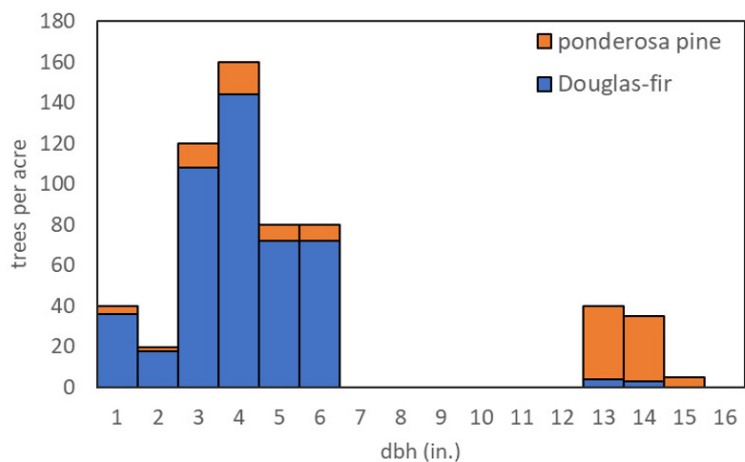


Figure 4.27—A planimetric view of existing condition Type 4. Smaller, lighter points identify seedlings, saplings and understory trees belonging to the second cohort.

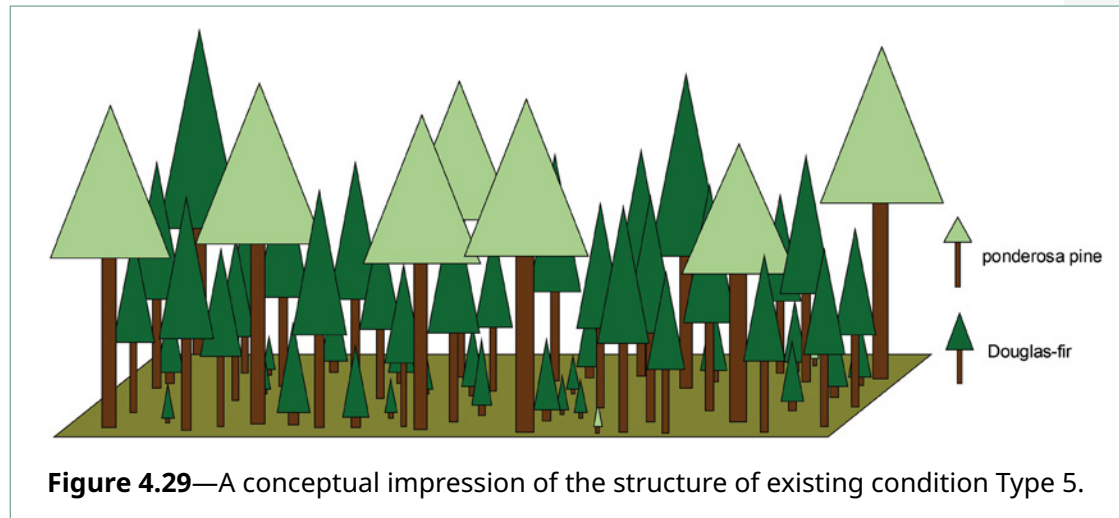
Figure 4.28—An example diameter distribution of existing condition Type 4 for a stand in the *Pseudotsuga menziesii* habitat type series. The younger cohort now comprises the majority of total stems per acre and exhibits a wide range of sizes, indicating a drawn-out phase of establishment and/or widely varying understory growing conditions and competitive environment.



Stand Summary	
Species	PIPO, PSME
Age (years)	120
Age structure	Two-aged
Stratification	Two-storied
QMD (in.)	6
Trees per acre	580
Basal area (ft ² ac ⁻¹)	128
SDI	249

Table 4.4—Example structural characteristics of existing condition Type 4 for a stand in the *Pseudotsuga menziesii* habitat type series. Acronyms follow notes to table 4.1.

Existing condition Type 5: old-growth stand with post-fire-exclusion ingrowth of shade-tolerant-species—



Existing condition Type 5 represents the densification of old-growth ponderosa pine stands, likely resulting from fire exclusion, the absence of cultural burning, and grazing. Large older trees are dominantly ponderosa pine, often with lesser amounts of western larch and Douglas-fir, depending on the site. Smaller shade-intolerant trees of pre-suppression origin often exist in the midstory. These pre-suppression remnants are now embedded in a dense matrix of younger trees and saplings, predominantly Douglas-fir or grand fir, that occupies the understory and midstory. High stand densities have reduced growth rates, and because of their low vigor, trees in all canopy layers are succumbing to mortality under the combined influence of competition and external stressors like drought, insects, and pathogens (depending on the site).



Figure 4.30—An aerial image of a stand conforming to existing condition Type 5.



Figure 4.31—A midstory view of existing condition Type 5. Although the height to the base of the live crown in this stand exceeds 66 ft (20 m), midstory and understory trees of a variety of sizes now create vertical fuel continuity around the base of the older trees. This increases the risk of torching in the pre-settlement cohort if a fire were to occur.

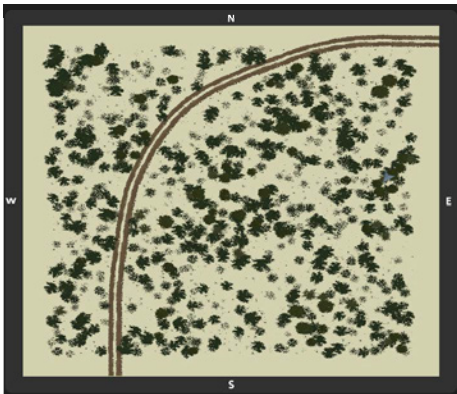
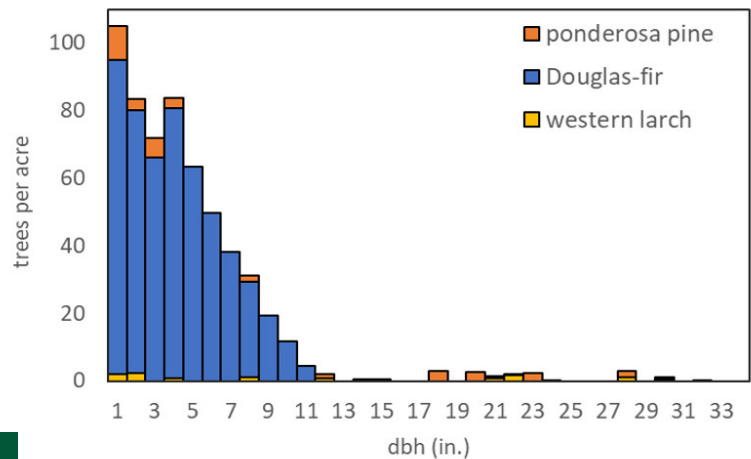


Figure 4.32—A planimetric view of existing condition Type 5. A wide range of tree ages and sizes are present. The density of the post-fire exclusion ingrowth, some of which are now relatively large, masks the spatial pattern of residual old-growth trees in this figure.

Figure 4.33—An example diameter distribution of existing condition Type 5 for a stand in the *Pseudotsuga menziesii* habitat type series. An almost continuous diameter range of ingrowth indicates a protracted phase of establishment in the absence of major disturbances, while the larger trees in the stand represent many different pulses of regeneration and exhibit a wide range of diameters.



Stand Summary

Species	PIPO, PSME, LAOC
Age (years)	300+
Age structure	Uneven-aged
Stratification	Multi-storied
QMD (in.)	6
Trees per acre	580
Basal area (ft ² ac ⁻¹)	120
SDI	225

Table 4.5—Example structural characteristics of existing condition Type 5 for a stand in the *Pseudotsuga menziesii* habitat type series. Acronyms follow notes to table 4.1.

Chapter 5: Desired Future Conditions

Describing the Range of Desired Future Conditions

The desired future condition is the intended structure and composition of the stand following successful transformation. It is a target for the transformation process and the structure that achieves the management objectives for the stand. Along with the existing stand condition, available resources, and management objectives, the desired future condition helps determine an appropriate sequence of transformation treatments. As the endpoint of the transformation process, the stand described in the desired future condition should also have a sustainable structure that can be maintained (within some range of conditions) over the long-term using multi-aged stocking control methods.

The time horizon over which the desired future condition may be attained is related to the degree of difference between the existing and desired future structures, as well as fundamental site factors and management choices. When the difference between existing and desired future conditions is small, for example, where the existing condition is a mature even-aged stand, the desired future condition is a relatively simple two-aged structure, and site productivity is high, the desired future condition may be reached in 20–30 years.

By contrast, where there is a substantial gap between existing and desired future conditions, and/or on sites with low growth rates or infrequent episodic regeneration, transformation may take many decades or more than a century. In this situation, developing short- and medium-term milestones can provide direction and assist in monitoring progress toward the desired future condition. This may help overcome institutional reluctance over seemingly open-ended, long-term endeavors. These milestones might consist of brief descriptions of the expected intermediate structures during the transformation process. However, silvicultural transformation, particularly to complex structures, involves uncertainty (chapter 3). This uncertainty should be reflected in the descriptions of intermediate structural milestones in written prescriptions and communications to other stakeholders.

Tailor the description of desired future conditions to the preferences and needs of the practitioners responsible for treatment design and implementation. Quantitative descriptions provide easily interpreted targets for determining treatment success and are consistent with the outputs of modeling software commonly used in projecting stand development. They also provide a reference for the marking guides used in transformation treatments. However, quantitative stand descriptions have

The description of desired future conditions should be tailored to the preferences and needs of practitioners responsible for treatment design and implementation.

limitations and may lack the flexibility needed to fully characterize stand structure.

Qualitative descriptions provide more flexibility than quantitative descriptions and can capture attributes of the desired future condition that are challenging or impossible to quantify. The Free Selection silvicultural system emphasizes qualitative descriptions of the desired future condition for this reason (Graham et al. 2006; Graham and Jain 2005). Specifying the desired future condition in these terms allows for the design of extremely complex structures across multiple spatial scales.

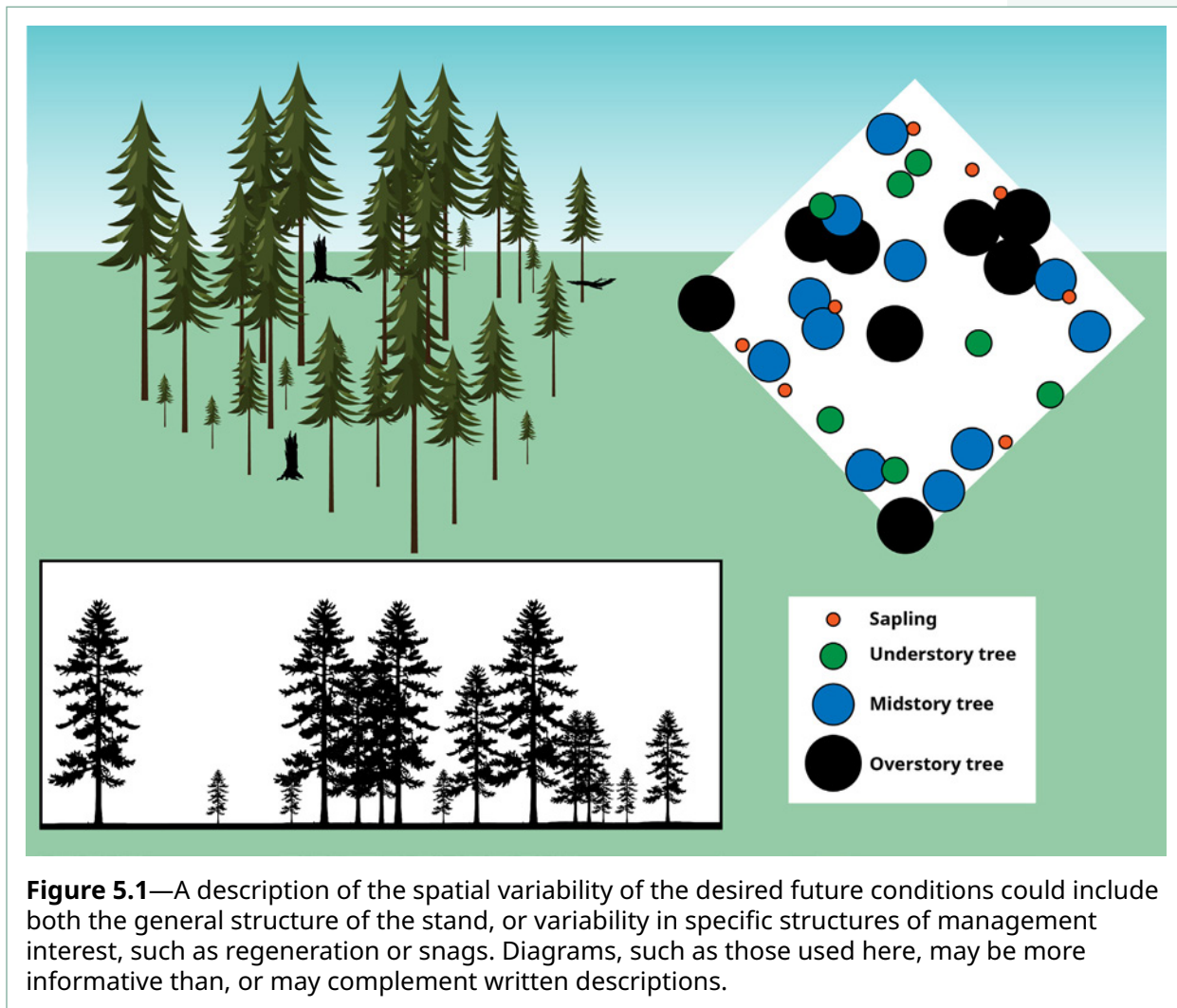
In practice, qualitative and quantitative descriptions are compatible. Blending these two forms of data can provide flexibility while retaining the numerical sideboards that many practitioners find useful. Likewise, many graphical presentation formats can be incorporated into the description of desired future conditions, including charts, diagrams and sketches, and simulation model outputs. Graphics may be particularly helpful when attempting to convey spatial or temporal variability in important structural attributes.

The structural elements (e.g., live trees, snags, coarse woody debris) to include in the description of desired future conditions and the variables that are used for each element (e.g., DBH, relative density) will vary according to site characteristics and management objectives. Most descriptions of desired future conditions will include some or most of the following structural elements:

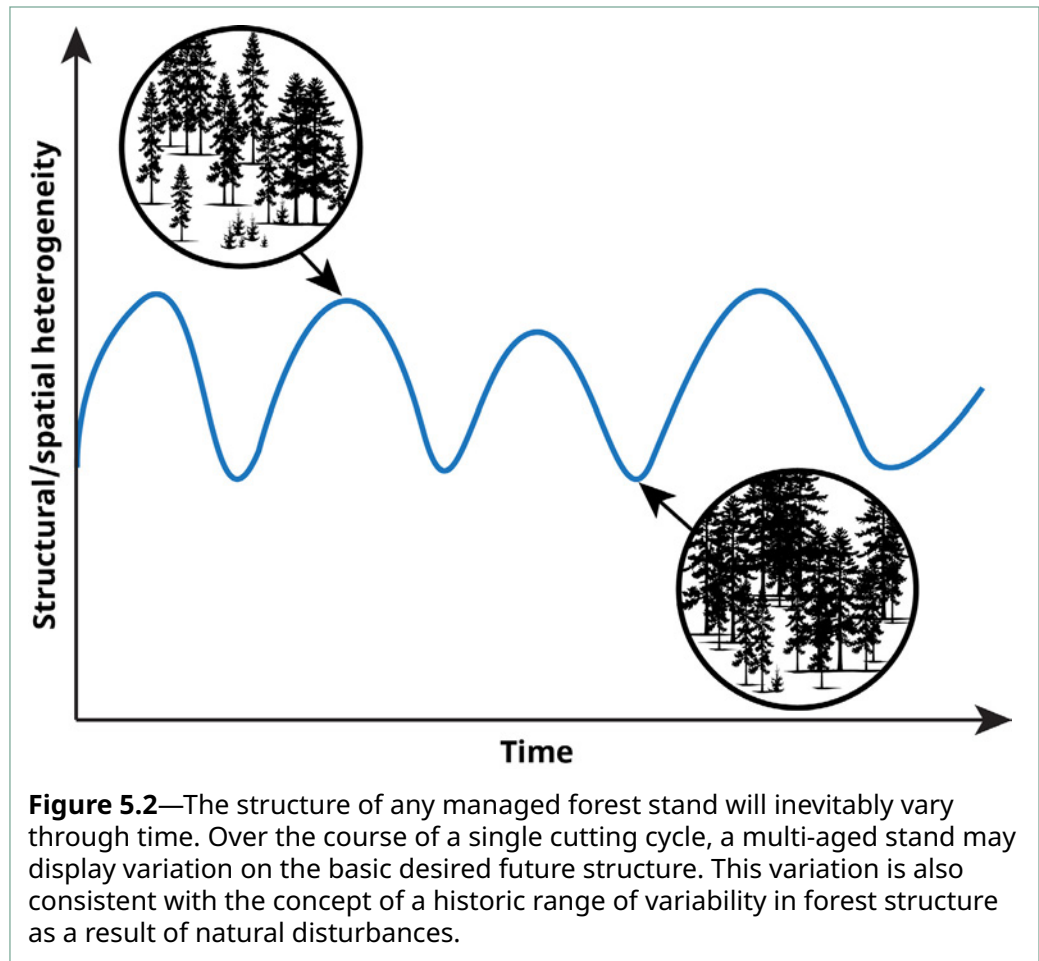
- Live trees in all canopy layers
- Saplings and regeneration
- Shrubs and herbaceous vegetation, including bryophytes on some sites
- Snags
- Dead woody surface fuels
- Spatial variability, or pattern, in each of the above elements, including the relationship of each element to other elements
- Openings within the stand
- Key ecological processes relevant to stand management objectives, such as mortality rates, interaction with disturbances, carbon accretion or stability, etc.

Regardless of whether the desired future condition is defined quantitatively or qualitatively, describing the expected within-

stand spatial variability in structure or specific structural elements (e.g., large live trees) is advisable (fig. 5.1).



Another important consideration when defining a desired future condition is temporal variability. The desired future condition of a multi-aged stand has been described as a “moving target” (O’Hara 2014) due to the expected changes in stand structure over a cutting cycle (fig. 5.2).



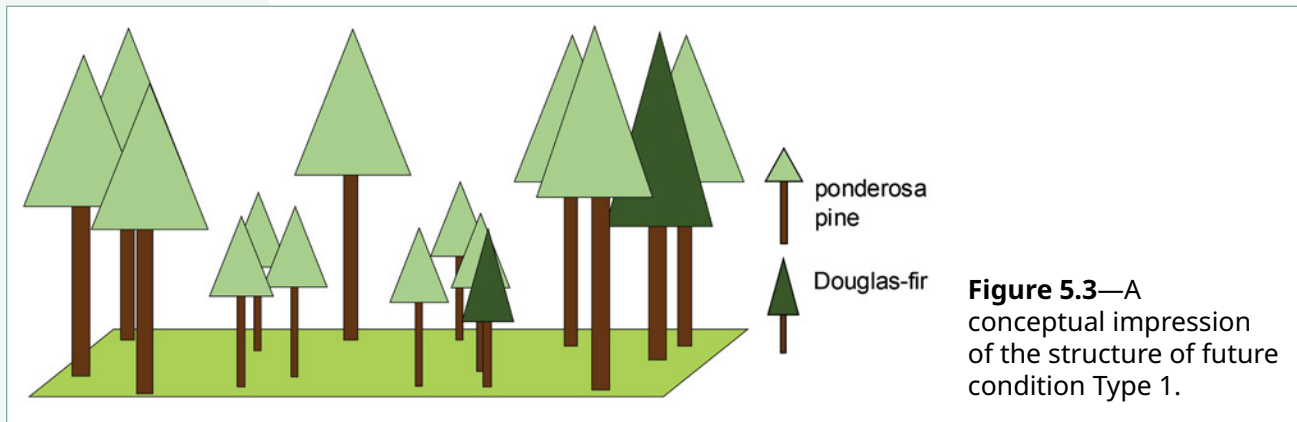
An alternative expression of this expected temporal variability in structure is a *range*, within which a future structure is expected to fluctuate. This perspective is encapsulated in the concept of a *historic range of variability* in forest or landscape structure (Keane 2013; Keane et al. 2009), which is now widely used in the literature on ecological restoration and disturbance ecology. The concept of a range is also useful in attempting to capture the influence of uncertain changes in future climate and growing conditions on forest structure and composition, sometimes referred to as the *future range of variation* (Churchill et al. 2022). Integrating these perspectives on temporal variability and uncertainty into the desired future condition can be achieved by reframing the target as a *range of desired future conditions*, which can be expressed using numerical ranges for quantitative data and equivalent descriptive language for qualitative data.

Generalized Examples of Future Conditions

A broad continuum of desired future conditions will exist for ponderosa pine forests in the northern Rocky Mountains, ranging from relatively simple two-aged structures to more complex uneven-aged structures. The following section generalizes some of these potential future conditions into six discrete future condition types, paralleling the approach used in chapter 4 to define existing condition types. The desired future condition types described below should not be interpreted as a finite list of realistic, desirable endpoints for the transformation. Instead, these examples describe generalized structural types that may be perpetuated by different multi-aged management regimes. Although many different multi-aged systems and methods can be used to create a given structure, some management regimes are more or less suited to sustaining different structures on a given site. Equally important, as described in chapter 6, the list of multi-aged regeneration harvest methods and stocking control practices that may be applicable in ponderosa pine stands is long, and includes practices that span a wide range of implementation complexity (or simplicity) and flexibility (or rigidity). Future condition Types 1–6 were intentionally devised to illustrate the potential result of applying a variety of these regeneration harvest methods and stocking control practices (identified below in the description of each condition type). Refer to chapter 6 for a more detailed discussion of these management approaches and their utility in ponderosa pine stands.

Each future condition type described below includes a visual depiction of the generalized structure and an example diameter distribution and structural summary for a hypothetical stand that conforms to this condition type. Numerical ranges illustrate how the summary metrics might appear in a description of a range of desired future conditions. These summaries are provided for demonstration purposes and are not a complete enumeration of the plausible numerical values for each attribute in stands conforming to each future condition type.

Future condition Type 1: mid-successional, two-aged structure—



Future condition Type 1 represents a relatively simple two-aged structure, with the older cohort maintained until mature ages (at least 80 years). Ponderosa pine is the dominant species in both cohorts. Stands in future condition Type 1 could be managed using irregular shelterwood or variable retention silvicultural systems. Although the example illustrated here involves an aggregated (i.e., grouped) pattern of overstory retention, dispersed retention could also be used, so long as understory light levels are sufficient to regenerate the younger cohort of ponderosa pine. Minor proportions of shade-tolerant species could be included in future condition Type 1 to increase compositional diversity, but this requires careful management of the spatial distribution of mature trees of these species and any ongoing regeneration.

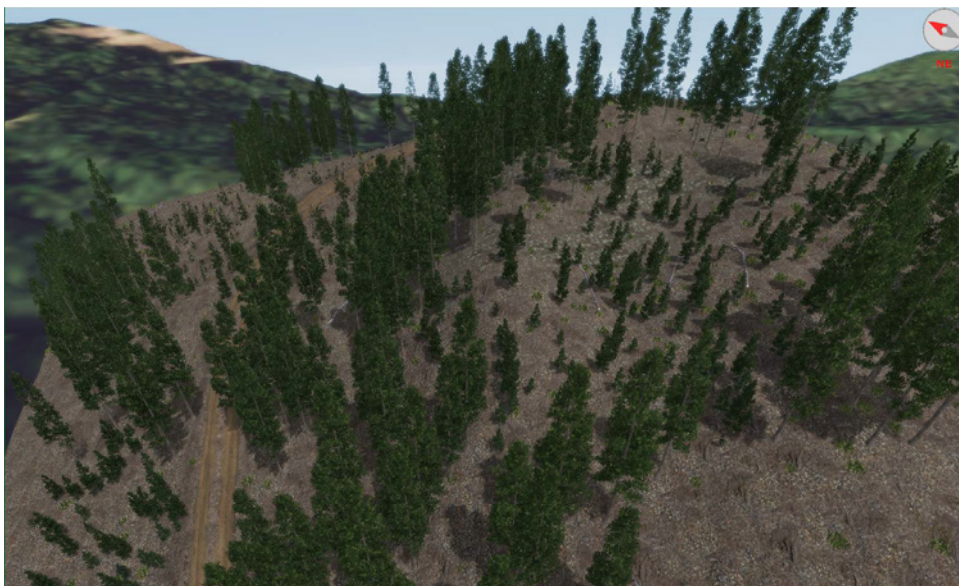


Figure 5.4—An aerial view of a stand conforming to future condition Type 1 during the decades following regeneration harvest. Harvesting in this stand used aggregated overstory retention to create spatial separation between cohorts.

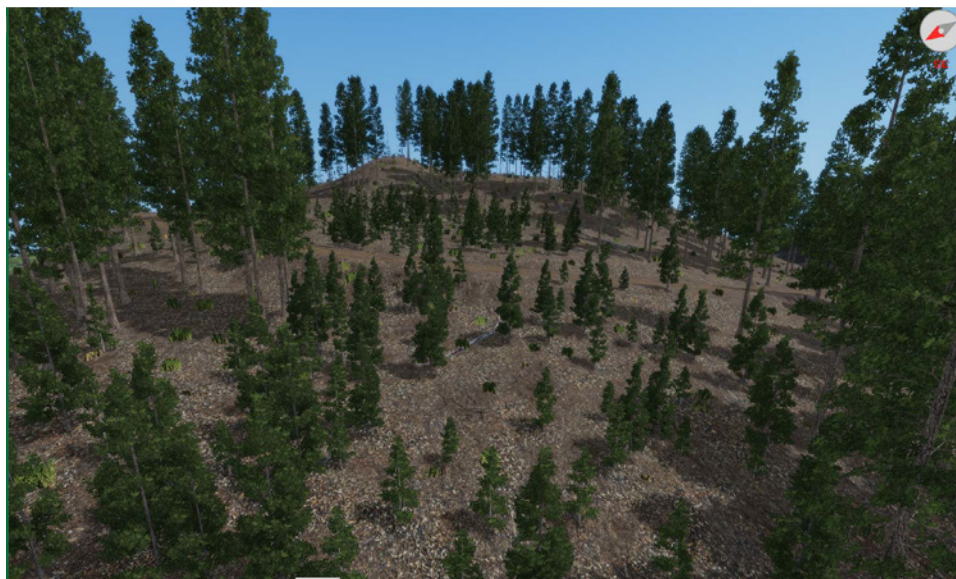


Figure 5.5—A midstory view of a stand conforming to future condition Type 1. Aggregated harvesting in this example has created large openings that provide high light availability to regeneration in the understory.

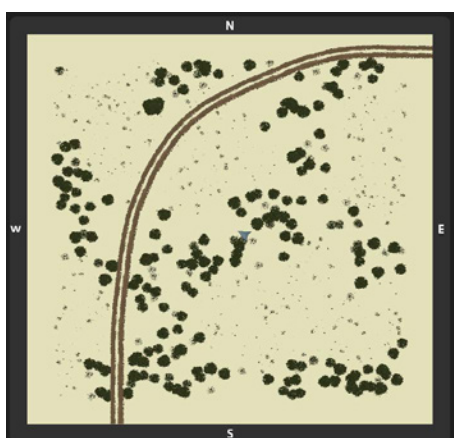


Figure 5.6—A planimetric view of future condition Type 1. Harvest openings are irregularly-shaped to increase complexity and reduce the hard edges that increase wind hazard.

Table 5.1—Example structural characteristics for a stand that conforms to future condition Type 1.

Stand Summary	
Species	PIPO, PSME
Age (years)	≥ 80
Age structure	Two-aged
Stratification	Two-storied
QMD (in.)	6 - 9
Trees per acre	180 - 250
Basal area (ft ² ac ⁻¹)	50 - 80
SDI	80 - 130

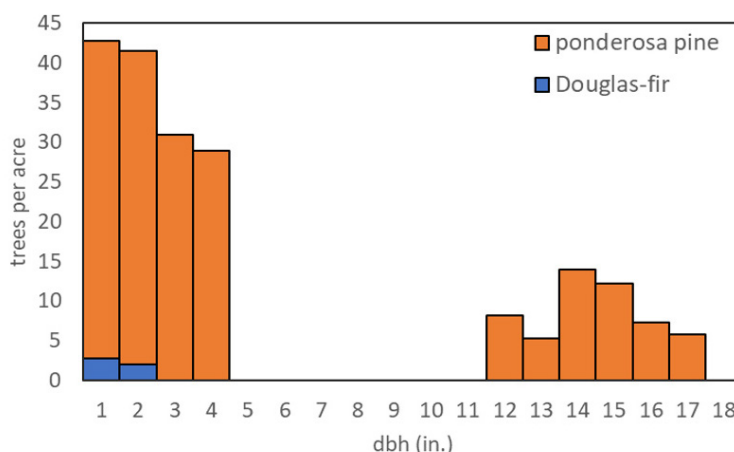
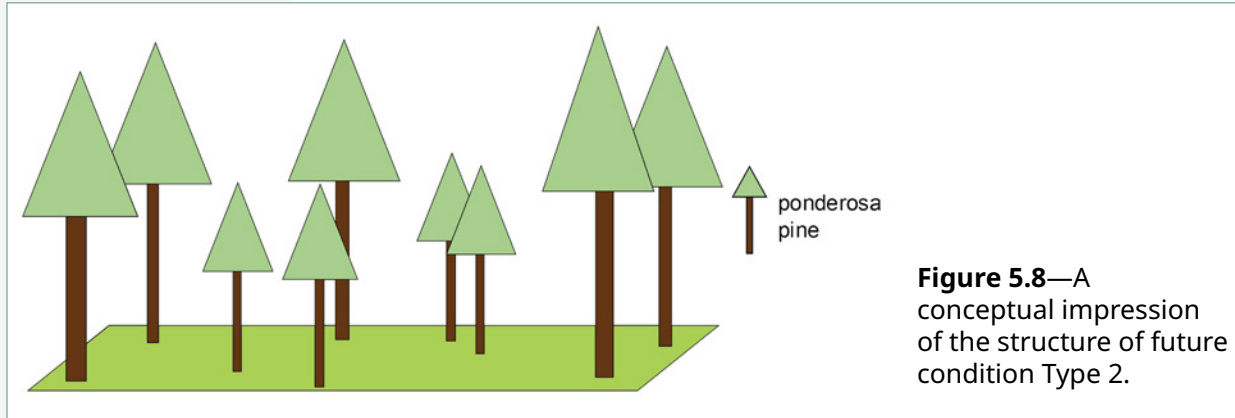


Figure 5.7—An example diameter distribution of future condition Type 1 for a stand in the *Pseudotsuga menziesii* habitat type series during the decades following an irregular shelterwood harvest.

Future condition Type 2: mid-successional, low density two-aged structure—



Future condition Type 2 is like future condition Type 1, but stem density is lower in both overstory and understory cohorts. This structure is particularly suited to stands on especially dry sites and those with elevated fire hazard because of topography or landscape context. On these sites, shifting composition to pure ponderosa pine or pine and western larch may best achieve resilience objectives, depending on the risk factors. Where the existing condition included more mesic and less fire-tolerant species, a shift toward pine dominance in the future condition may be a climate adaptation strategy. Compared to future condition Type 1, stands conforming to Type 2 will typically exhibit wider tree spacing, on average, and larger openings. However, Type 2 may still feature aggregated (grouped) retention patterns and relatively small (< 2 acres) openings, for example, to help moderate soil surface conditions for seedling development.

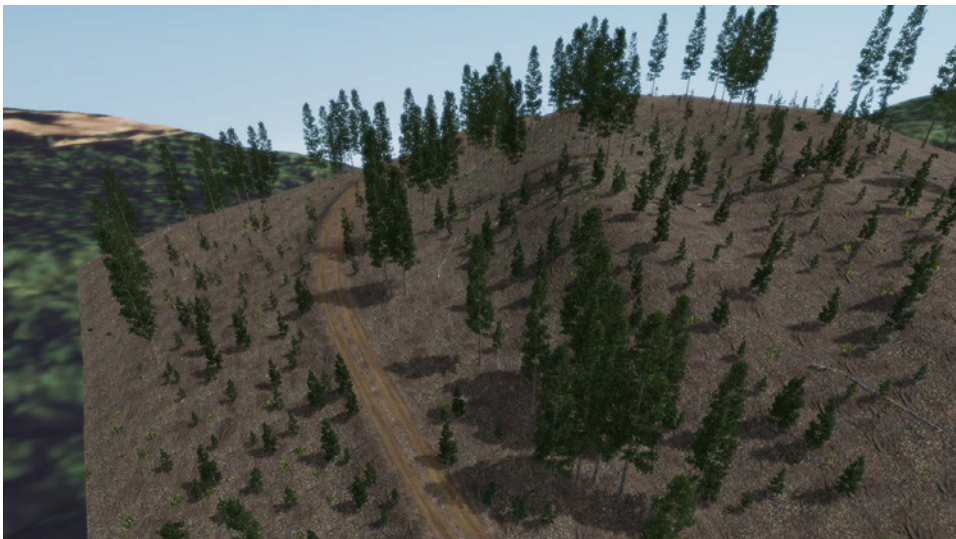


Figure 5.9—An aerial view of a stand conforming to future condition Type 2 during the decades following regeneration harvest. Stand density is much lower than in future condition Type 2.

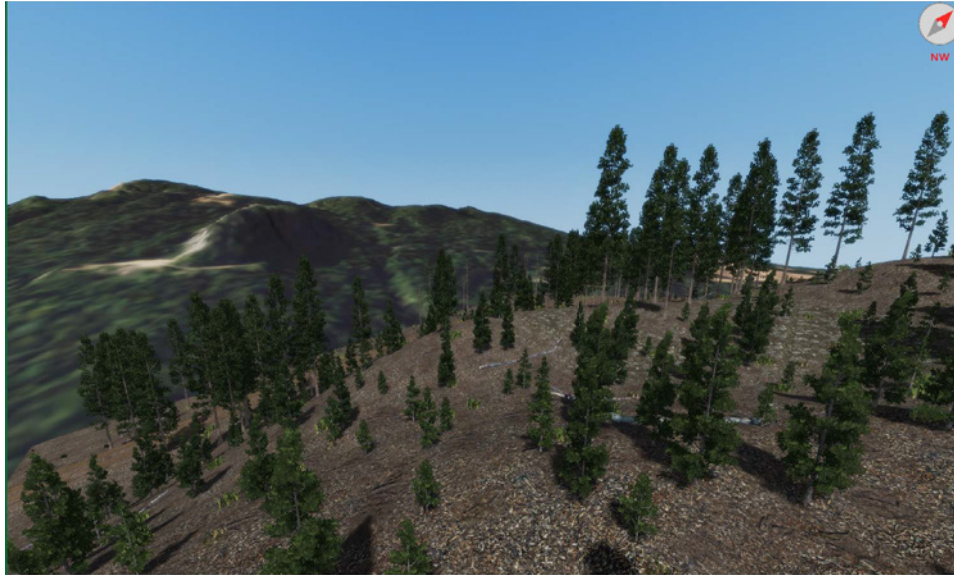


Figure 5.10—An understory view of a stand conforming to future condition Type 2 during the decades following irregular shelterwood harvest. In this example, lower residual overstory density creates a more open, lighter environment that should increase resource availability to support regeneration.

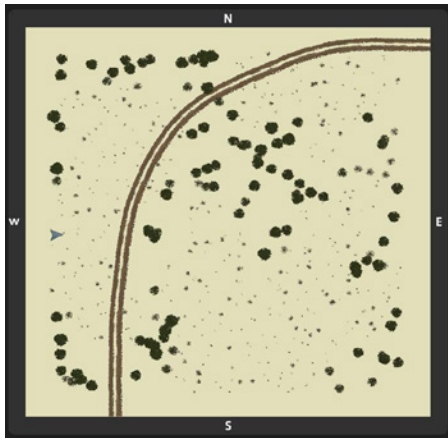


Figure 5.11—A planimetric view of future condition Type 2. Harvest openings are more irregularly-shaped than in future condition Type 1 in order to increase micro-climate amelioration for seedlings despite the lower residual density in the overstory.

Table 5.2—Example structural characteristics for a stand that conforms to future condition Type 2.

Stand Summary	
Species	PIPO
Age (years)	≥ 80
Age structure	Two-aged
Stratification	Two-storied
QMD (in.)	6 - 9
Trees per acre	90 - 130
Basal area (ft ² ac ⁻¹)	20 - 55
SDI	40 - 110

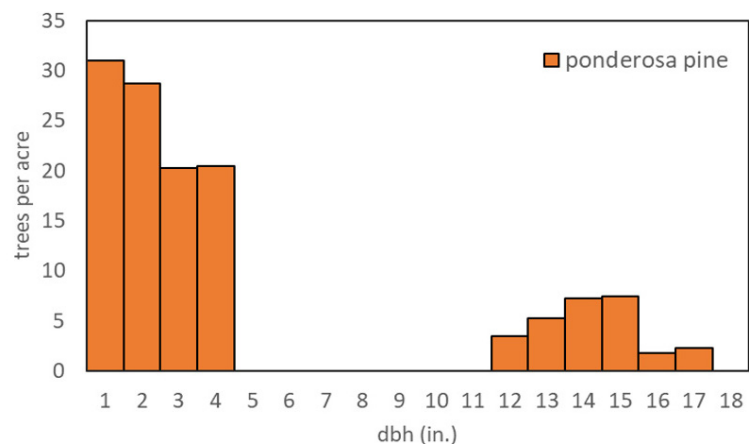
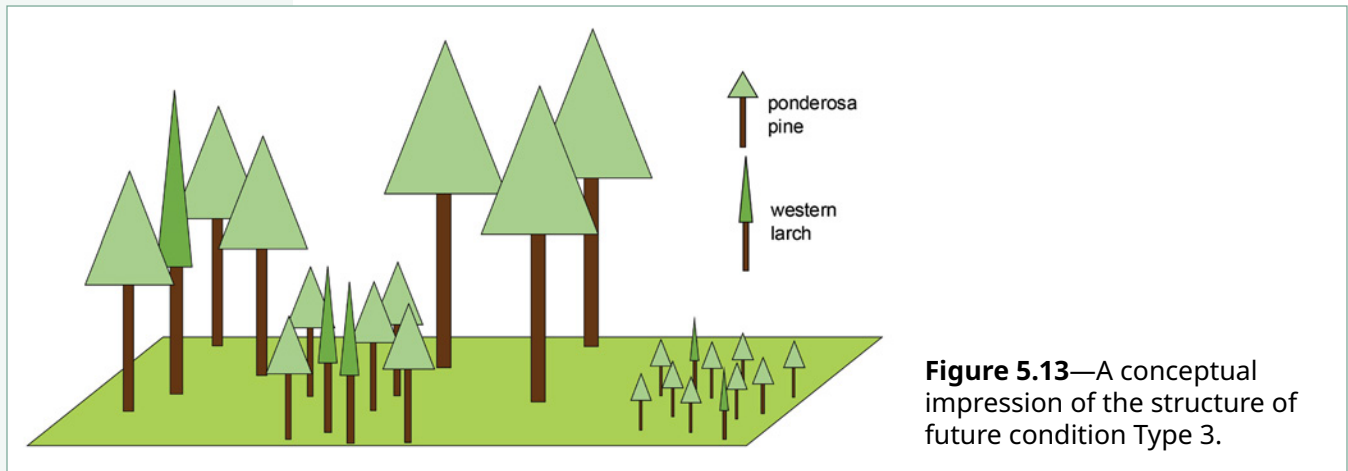


Figure 5.12—An example diameter distribution of future condition Type 2 for a stand in the *Pseudotsuga menziesii* habitat type series during the decades following an irregular shelterwood harvest.

Future condition Type 3: area control, regulated, uneven-aged structure—



Stands in future condition Type 3 have a relatively complex, multi-cohort (three to five) age-class structure, but do not involve an intimate spatial mixing of these cohorts. Instead, each cohort occupies distinct patches of approximately equal area within the stand. The spatial configuration of these patches can vary widely. Geometric patch shapes may increase simplicity in marking, harvesting, and tracking cohorts through time, while less geometrically-shaped patches resemble the natural patterns and processes of forest development. In the example presented here, patches are relatively large (up to 2 acres) to promote regeneration of ponderosa pine and, depending on the site, western larch. Future condition Type 3 could be maintained using an area control approach to growing stock regulation in a multi-aged silvicultural system involving group selection or irregular shelterwood harvests (see chapter 6).





Figure 5.15—An understory view of a stand conforming to future condition Type 3. The cohort in the foreground established following regeneration harvest in the last decade.

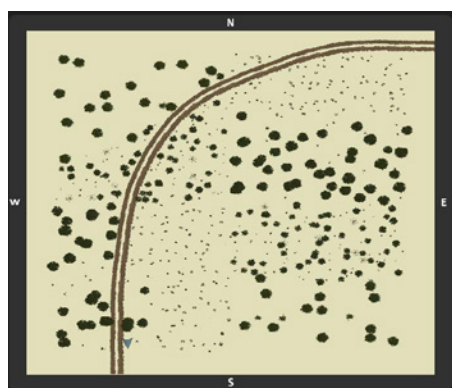


Figure 5.16—A planimetric view of a stand conforming to future condition Type 3. In this example, cohorts of different age are highlighted as differently-sized points, arrayed in geometric-shaped patches across the stand.

Table 5.3—Example structural characteristics for a stand that conforms with future condition Type 3.

Stand Summary	
Species	PIP0, LAOC
Age (years)	≥ 120
Age structure	Uneven-aged
Stratification	Multi-storied
QMD (in.)	6 - 9
Trees per acre	100 - 150
Basal area (ft ² ac ⁻¹)	20 - 65
SDI	50 - 125

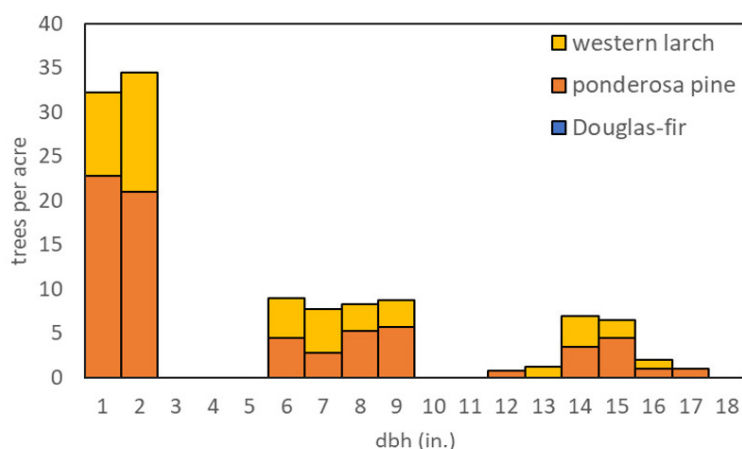
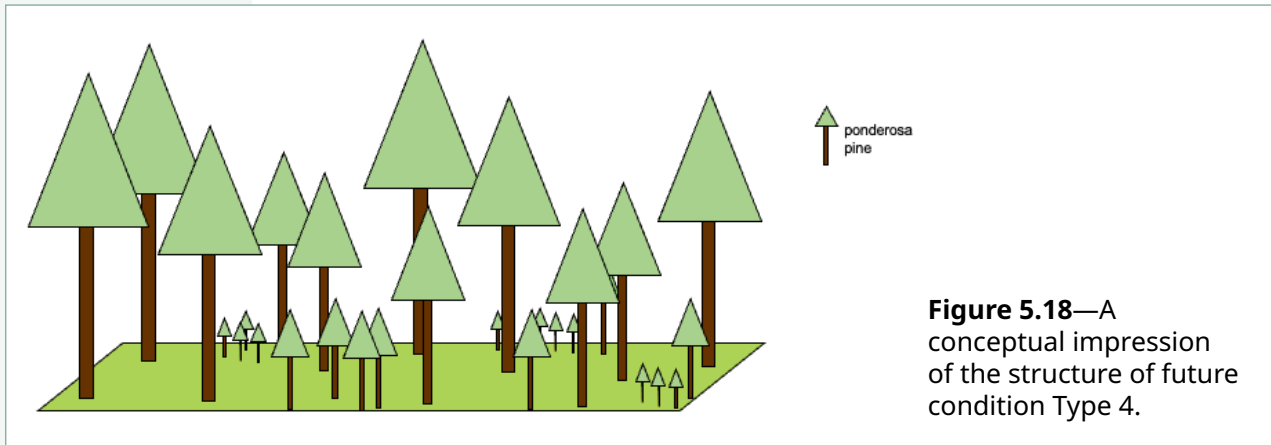


Figure 5.17—An example diameter distribution of future condition Type 3 for a stand that is composed of ponderosa pine and western larch. The distribution is suggestive of three distinct age-classes.

Future condition Type 4: balanced, uneven-aged structure—



Future condition Type 4 is a regulated, uneven-aged stand with three to five cohorts (including seedlings) and a balanced distribution of stems across diameter classes. There is more heterogeneity and intermixing in the spatial distribution of cohorts across the stand than in future condition Type 3. Regeneration is primarily small-gap-based with management actions attempting to ensure some spatial separation between understory and overstory to reduce fire hazard. While ponderosa pine is the dominant species in all cohorts, this dominance will be challenging to achieve or maintain on some sites, especially those in the *Abies grandis* habitat type series and the wetter end of the *Pseudotsuga menziesii* series. In a multi-aged silvicultural system, the balanced structure of this future condition type is best maintained using the BDq (see box 4) or SDI allocation methods of stocking control (see chapter 6).

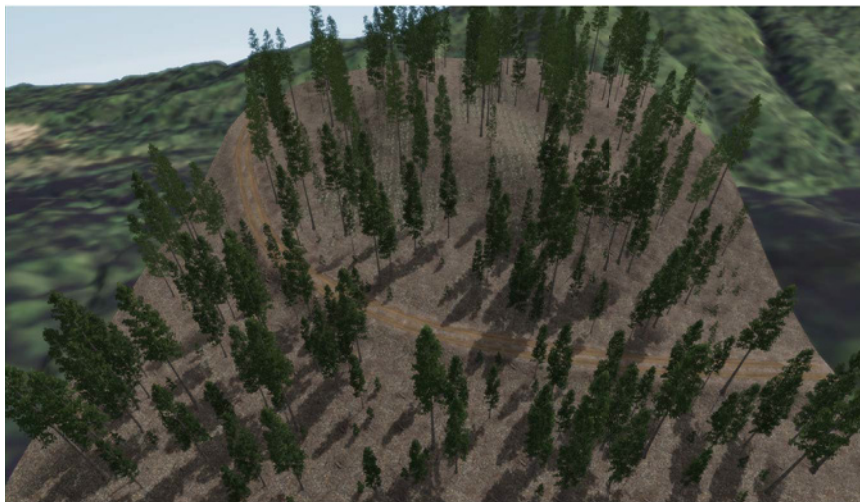


Figure 5.19—An aerial view of a stand conforming to future condition Type 4. Age classes are intermingled, with establishment in canopy gaps facilitated by lower stand density than all existing condition types.



Figure 5.20—An understory view of a stand conforming to future condition Type 4. Multiple age classes, from seedlings to mature overstory trees, are visible in this small area of the stand.

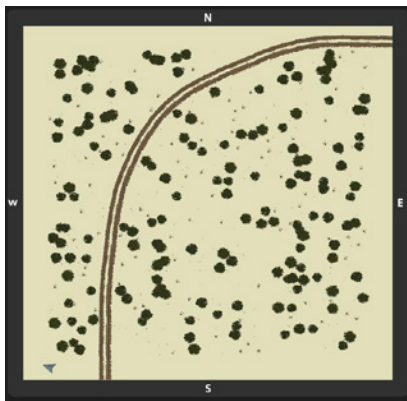


Figure 5.21—A planimetric view of a stand that conforms to future condition Type 4. A spatially heterogeneous distribution of seedlings and trees of all sizes is evident. Seedlings (smaller points) have established predominantly, although not exclusively, in canopy gaps created by harvesting.

Table 5.4—Example structural characteristics for a stand that conforms with future condition Type 4.

Stand Summary	
Species	PIPO
Age (years)	≥ 160
Age structure	Uneven-aged
Stratification	Multi-storied
QMD (in.)	10 - 12
Trees per acre	100 - 120
Basal area (ft ² ac ⁻¹)	40 - 95
SDI	75 - 160

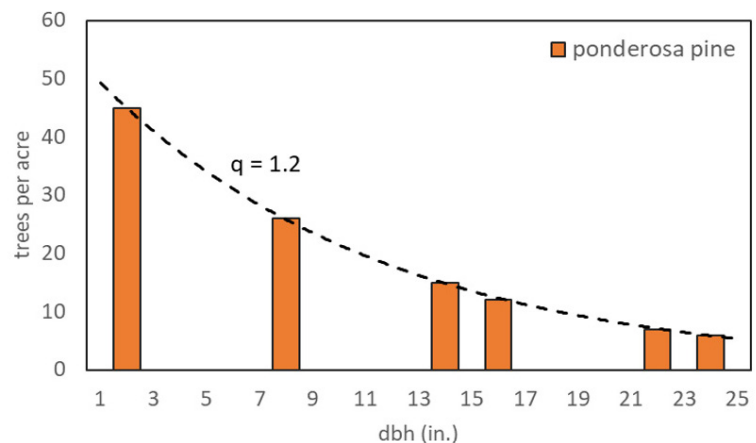
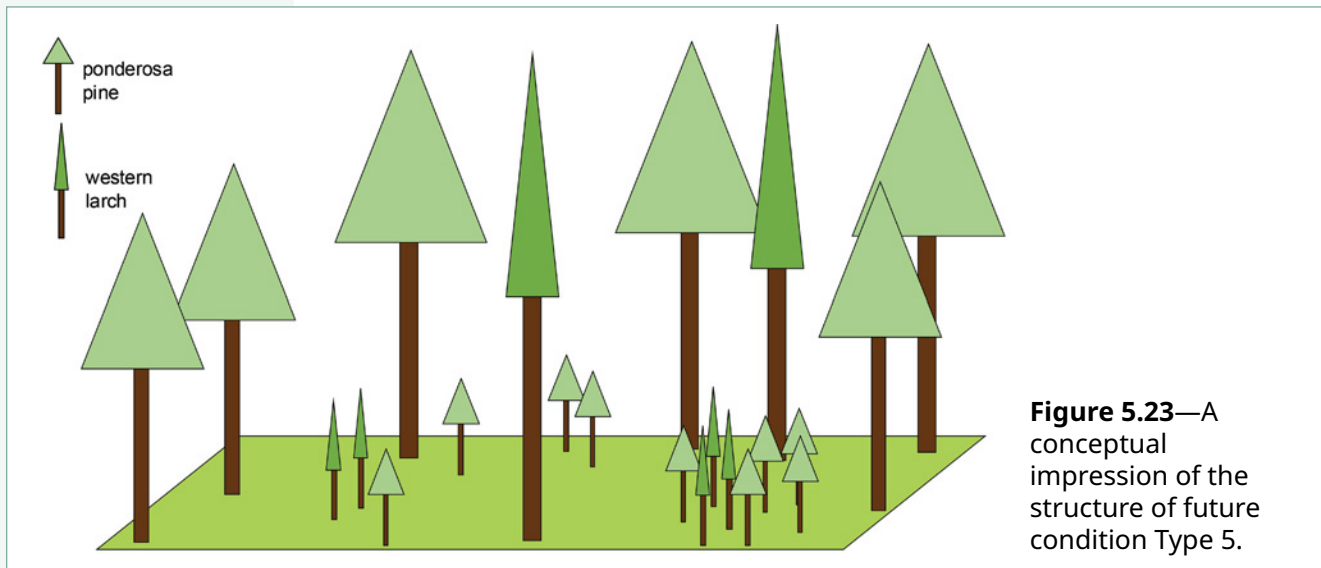


Figure 5.22—An example diameter distribution of future condition Type 4. In this example, the stand is pure ponderosa pine, reflecting the fact that maintaining a balanced age-class distribution in uneven-aged stands using single-tree selection is likely to be easiest on sites in the ponderosa pine habitat type series. In this example, a BDq method of stocking control is used, with a 24-inch upper diameter and a q-factor of 1.2.

Future condition Type 5: unbalanced, uneven-aged structure—



Future condition Type 5 is a stand with three or more age classes dominated by shade-intolerant species. The growing stock is not balanced—and is perhaps very far from balanced—across cohorts. The diameter distribution, structure, and spatial pattern of stands in this condition type is inherently variable, both from stand to stand and through cutting cycles in a single stand and may not conform with any conventional silvicultural specifications. Future condition Type 5 is an example of a structure that could be produced and maintained by a “light-touch” multi-aged management regime. Under this regime, stocking control is applied loosely with the primary objective of simply ensuring that sufficient regeneration of ponderosa pine occurs following harvests to eventually replace the oldest cohort in the stand (see chapter 6).

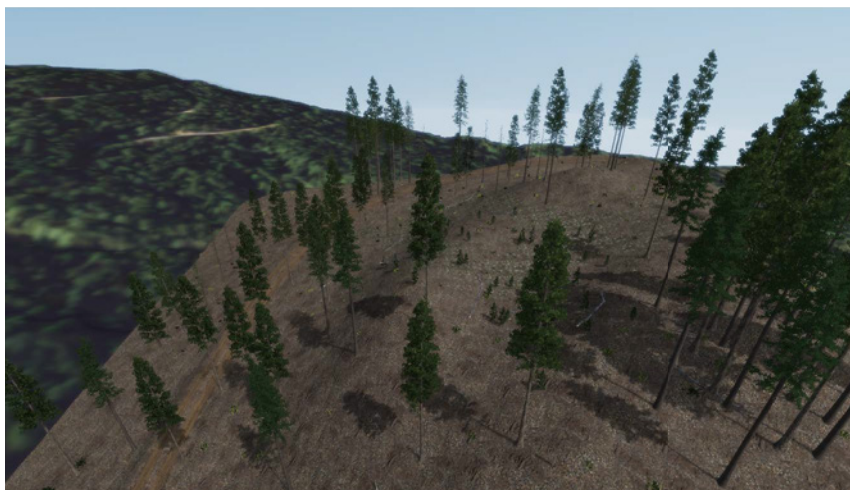


Figure 5.24—An aerial view of a stand conforming to future condition Type 5. The characteristic feature of this future condition type is the uneven allocation of growing space and uneven age gaps between cohorts.



Figure 5.25—An understory view of a stand conforming to future condition Type 5. In this example stand, there are no midstory trees, a legacy of the unbalanced age-class distribution. Instead, at least two mature overstory cohorts exist, and another cohort occupies the understory.

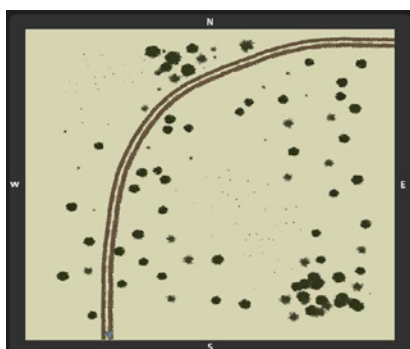


Figure 5.26—A planimetric view of a stand that conforms to future condition Type 5. In this example, a wide range of harvest gaps exist, from small canopy openings to larger areas resembling an aggregated irregular shelterwood.

Table 5.5—Example structural characteristics for a stand that conforms with future condition Type 5. The upper end of the tabulated basal area and SDI ranges are only applicable in stands with relatively high densities of very large, old trees (e.g., Arno et al. 1995).

Stand Summary	
Species	PIP0, LAOC
Age (years)	≥ 160
Age structure	Uneven-aged
Stratification	Multi-storied
QMD (in.)	8 - 14
Trees per acre	60 - 140
Basal area (ft ² ac ⁻¹)	20 - 150
SDI	40 - 240

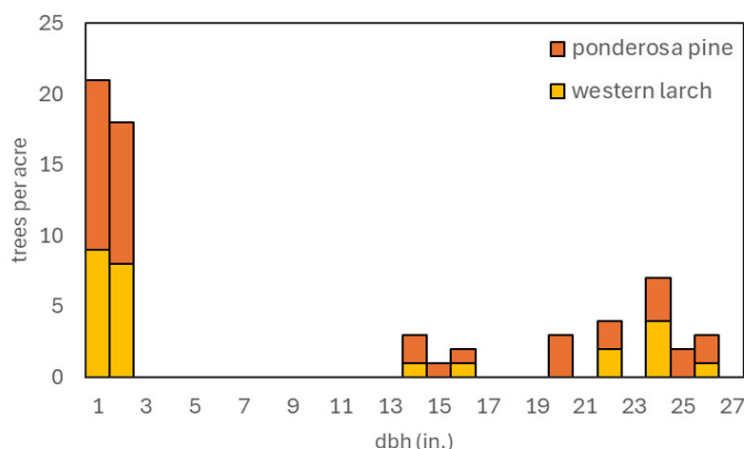


Figure 5.27—An example diameter distribution of future condition Type 5. This stand has at least two cohorts in the overstory, and one cohort of saplings.

Future condition Type 6: restored old-growth stand with uneven-aged structure—

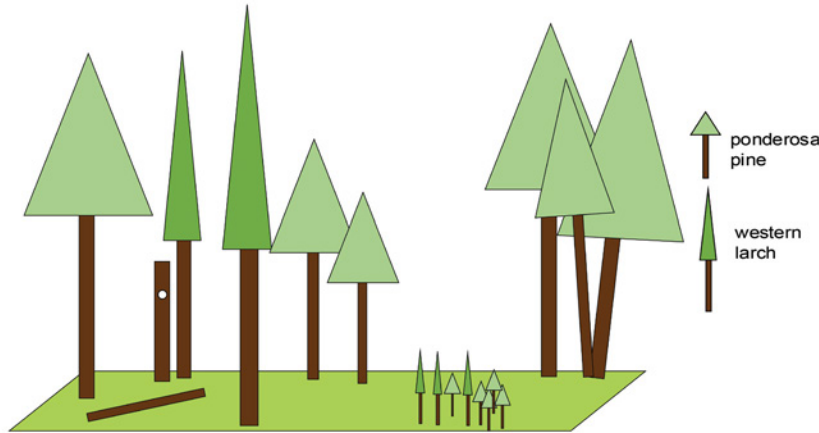


Figure 5.28—A conceptual impression of the structure of future condition Type 6.

Future condition Type 6 approximates the structure of historical ponderosa pine-dominated stands, pre-Euro-American settlement, and it could be a product of successful restoration in stands originating presettlement. This condition is variable from site to site and includes three or more age classes. Each age class is represented by a small number of stems per acre to produce a stand with relatively low overall stem density and, often, low basal area. The oldest cohort of trees may be of presettlement origin, but old trees may not always be the largest. Low densities of large snags and logs are also present. The spatial pattern of the stand is characterized by individual trees, clumps (of varying size) of trees, and openings (also varying in size). The diameter distribution may (or may not) resemble the reverse-J curve, but the distribution of growing stock between cohorts is unlikely to be balanced, and age gaps between cohorts will not be regular. In these respects, future condition Type 6 differs from the regular, balanced future condition Type 4. Future condition Type 5 may resemble condition Type 6 in spatial pattern, but the former may not include trees of the size and age present in condition Type 6 and may lack the spatial pattern typical of this condition type.



Figure 5.29—A view of the spatial distribution of trees in different cohorts in a stand conforming to future condition Type 6. In this condition type, the spatial pattern of large trees following transformation primarily reflects patterns of tree establishment before Euro-American settlement and associated changes in forest dynamics and disturbances.



Figure 5.30—An understory view of a stand conforming to future condition Type 6. Seedlings visible in the foreground have regenerated, without planning, in openings created during a restoration harvesting. In the background, a large snag retained for wildlife habitat is visible.

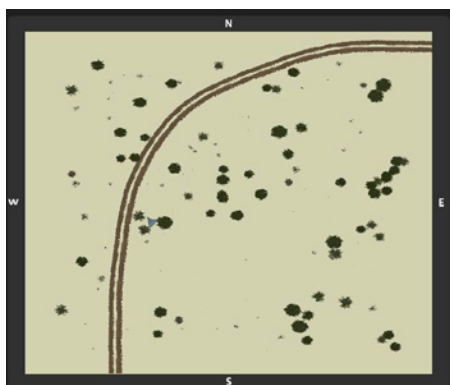


Figure 5.31—A planimetric view of a stand that conforms to future condition Type 6. The restored structure includes individual trees, a range of tree clump sizes and openings of varying size, including a large (> 1 acre) opening.

Table 5.6—Example structural characteristics for a stand that conforms with future condition Type 6. The upper end of the tabulated basal area and SDI ranges are only applicable in stands with relatively high densities of very large, old trees (e.g., Arno et al. 1995).

Stand Summary	
Species	PIPO, LAOC
Age (years)	≥ 200
Age structure	Uneven-aged
Stratification	Multi-storied
QMD (in.)	12 - 16
Trees per acre	50 - 140
Basal area (ft ² ac ⁻¹)	60 - 150
SDI	100 - 240

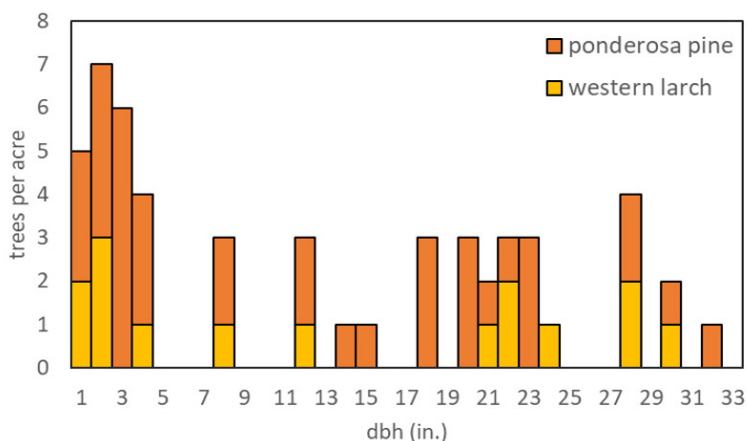


Figure 5.32—An example diameter distribution of future condition Type 6. The distribution of tree sizes is suggestive of many different cohorts, each of which recruits at extremely low density (stems per acre).

Chapter 6: Management Options

Chapter Guide

This is the toolbox chapter and contains written and visual information to assist with management choices using the “treatment card” approach. For navigation purposes, the content is presented in the following subsections.

Introduction: pages 88–91

Regeneration harvest methods: pages 91–101

Hybrid methods: pages 102–111

Intermediate treatments: pages 111–121

Multi-aged stocking control: pages 122–130

Cutting cycle: pages 131–135

Introduction

As emphasized elsewhere in this guide, there is no one-size-fits-all strategy for transforming even-aged ponderosa pine stands to multi-aged structures. No two stands will have the same site characteristics, existing and desired future conditions, and management objectives and constraints, so the transformation sequence will vary from one stand to the next. It is fortunate, then, that the range of management practices available to use in the transformation of ponderosa pine stands to multi-aged structure is also broad. These management options include the regeneration harvest methods that form the backbone of a multi-aged silvicultural system and are responsible for establishing new cohorts during the transformation process. Intermediate treatments are also extremely valuable during the transformation.

In many situations, transformation to a ponderosa pine-dominated structure is unlikely to be successful without intermediate treatments, such as improvement cutting, thinning, and prescribed burning or the mechanical equivalent. Then there are practices that may serve both regeneration and tending functions. These practices—which are referred to here to as hybrid methods—focus on modifying stand structure, for a variety of purposes, but also create conditions suitable for regenerating new cohorts. Collectively, the hybrid, intermediate, and regeneration harvest methods form the building blocks of the transformation sequence. Different combinations of treatments, treatment frequencies, and treatment applications create an almost limitless suite of transformation sequences to match the widely varying stand, site, and management needs.

Most practitioners are more familiar with managing ponderosa pine using even-aged methods rather than multi-aged methods, and this may lead to apprehension when contemplating transformation to multi-aged structures. However, it is useful (and hopefully reassuring!) to recall that many of the practices of tending even-aged stands are also used in multi-aged management and during silvicultural transformation. Similarly, the skills, knowledge of species silvics, and silvicultural intuition gained from practical experience of even-aged forestry are still relevant to the transformation to multi-aged structures and in subsequent multi-aged management. Implementing a multi-aged system doesn't mean throwing out existing tools and insights, but simply adding new ideas.

Implementing a multi-aged silvicultural system doesn't mean throwing out existing tools and insights, but simply adding new ideas.

Transformation from an even-aged to a multi-aged structure in ponderosa pine forests typically involves shifting from an even-aged silvicultural system to a multi-aged system, although the latter system may not always be formalized. Where transformation is taking place in a stand in which some form of harvesting is envisioned to meet long-term management objectives, implementation of a multi-aged silvicultural system will clearly be required to maintain the stand within the range of desired future conditions following transformation. In other situations, such as fire-excluded old-growth stands (existing condition Type 5, Chapter 4), restoration and maintenance of the assumed pre-settlement structure (for example, future condition Type 6, Chapter 5) may be the primary long-term management objective, with commercial harvesting either unimportant or not permitted. However, forests are dynamic, and restored structures will gradually revert to an overstocked condition in the absence of periodic low-severity disturbance. Therefore, although not formalized in a silvicultural system, planning for recurring maintenance burns (or their mechanical equivalent), and ensuring some degree of regeneration in stands that have been restored to a pre-settlement-like structure is wise. Figure 6.1 introduces the conceptual relationship between the transformation of stands to a multi-aged structure and their subsequent management. As this figure implies, the majority of silvicultural treatments that may have a role in the transformation process could also be applicable to the long-term management of multi-aged stands.

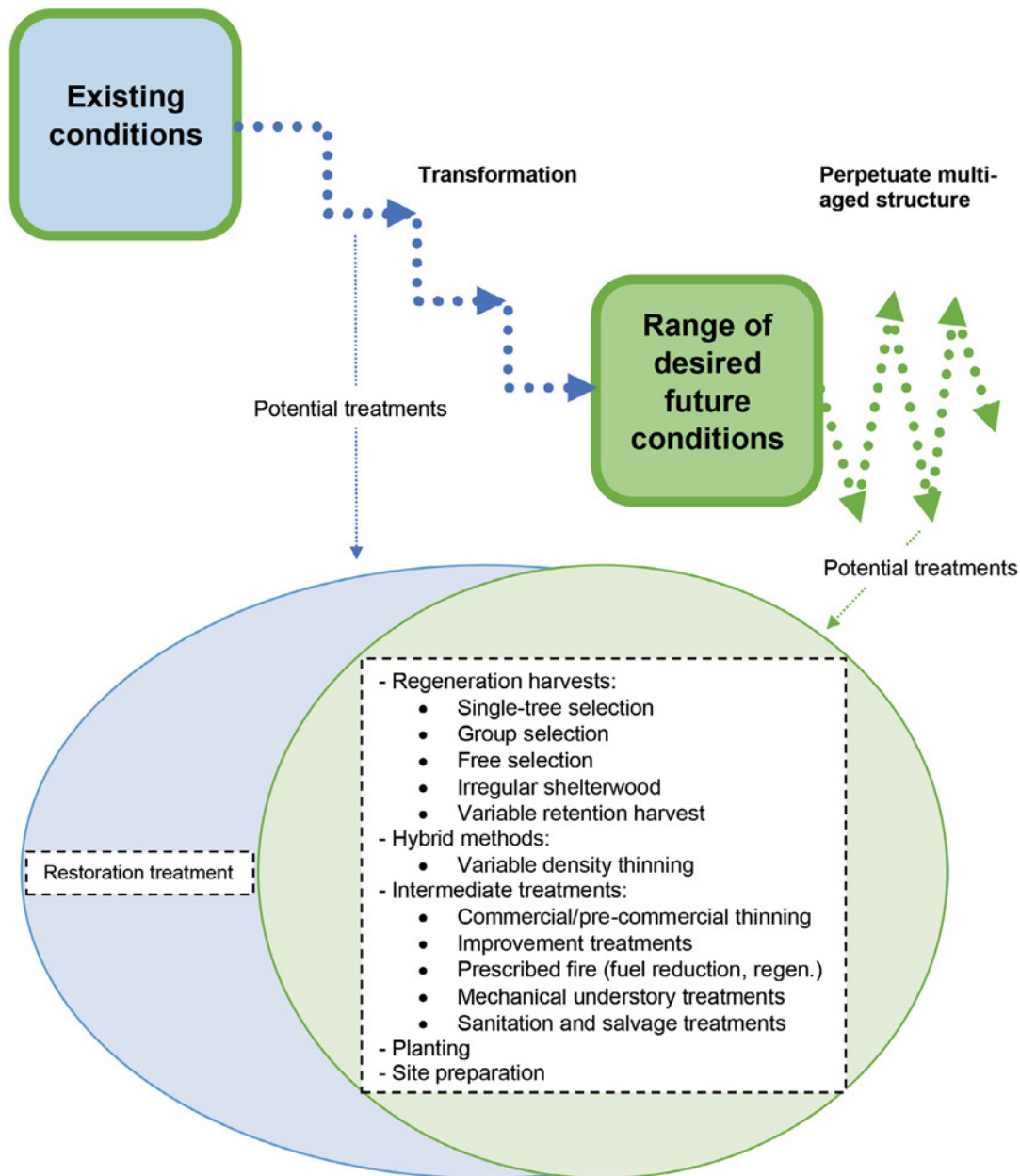


Figure 6.1—A conceptual depiction of the relationship between transformation and long-term multi-aged management. Except for restoration treatments, all treatments that have potential during the transformation sequence may also be used in perpetuating a multi-aged structure. Planting and site preparation are not covered in this document.

The rest of this chapter provides an overview of many regeneration harvest methods, hybrid methods, and intermediate treatments that may be useful in the transformation and subsequent long-term management of ponderosa pine stands. Treatment descriptions focus on the potential applicability to ponderosa pine stands, especially those in the northern Rocky Mountains. However, readers familiar with any of the individual practices may wish to skip these subsections.

Finally, we briefly discuss a variety of approaches to stocking control (or *growing stock regulation*) in multi-aged stands. Although implementing a specific stocking control method will not always be required during the transformation process, some form of stocking control is needed for the long-term management of multi-aged stands. Stocking control methods are introduced here for two reasons. First, transformation may be a challenging and lengthy process. Outlining a workable management regime capable of maintaining a sustainable, desirable structure over the long-term before starting this process can help reduce risk and save wasted time and effort. Second, textbook descriptions of multi-aged stocking control tend to focus on formal methods that may appear complex, rigid, and/or impractical. This may lead to the perception that multi-aged management in ponderosa pine is unattainable. By describing a wider variety of approaches, we hope to show that multi-aged stocking control practices can be as simple or as complex as the situation demands.

Multi-aged Regeneration Harvest Methods

There is a wide range of multi-aged regeneration harvest methods, offering considerable flexibility to produce two-aged (e.g., fig. 6.2) and uneven-aged structures, both simple and complex. Practices include both classical single-tree and group selection, as well as more recently described treatments, such as variable retention (or simply “retention”) harvest (e.g., Beese et al. 2019; Franklin et al. 1997). All of these methods are described in the following section.



Figure 6.2—Ponderosa pine seedlings regenerating in a gap following an irregular shelterwood harvest and subsequent broadcast burning in a managed ponderosa pine stand in western Montana.

Single-tree Selection (or Individual-tree Selection)

What Is It?

Single-tree selection harvests simultaneously create growing space for regeneration and tend existing growing stock by removing individual trees or small clumps of adjacent trees across age or diameter classes throughout the stand.

Regeneration Mechanism

- Germination and establishment of seed in canopy openings.
- Release of advanced regeneration in/near canopy openings.
- Compatible with planting to expedite and/or increase control over the recruitment process.

Utility in Transformation to Multi-Aged Structure in Ponderosa Pine Stands

Single-tree selection is most effective on ponderosa pine habitat types. Where ponderosa pine is seral, implementing single-tree selection will often be less effective and more resource-intensive. In the latter settings, small canopy gaps created during harvest create light conditions favorable to ponderosa's more shade-tolerant associates (if seed sources exist). This will gradually shift composition of the regeneration and sapling layer away from ponderosa pine in the absence of intervention to counteract the trend. This shift in composition is most likely when a single-tree selection harvest is implemented as the first step in a transformation sequence in a young, well-stocked stand. In older stands and those with more widely-spaced trees, removing individuals or small groups of trees will increase understory light availability for ponderosa pine establishment (see Case study 2, Lolo National Forest in chapter 8).

In all seral ponderosa pine stands, prospects for maintaining pine dominance may be increased by:

- Creating a limited number of small gaps (e.g., 0.10–0.25 ac) in addition to removing individuals or small clumps of trees (a group selection hybrid).
- Using low-intensity prescribed fire and/or mechanical treatments to remove shade-tolerant advanced regeneration before harvests. This is particularly important before the first selection entry in a transformation sequence.
- Prioritizing removal of shade-tolerant species during selection harvest or other intermediate treatments and retaining less growing stock overall.
- Planting ponderosa pine.

Limitations

- Difficulty maintaining dominance of ponderosa pine (or other desirable shade-intolerant species) alongside more shade-tolerant species in mixed stands.
- Relatively complex harvest planning is needed to avoid damage to residual growing stock (very small harvest gaps).
- Single-tree selection may produce a less heterogeneous spatial pattern than pre-settlement ponderosa pine forests.
- Single-tree selection will often increase vertical fuel continuity, especially in young stands (and marking to avoid this increases the complexity of marking).

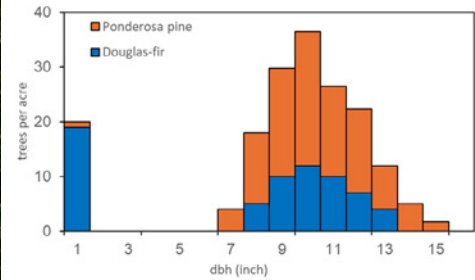
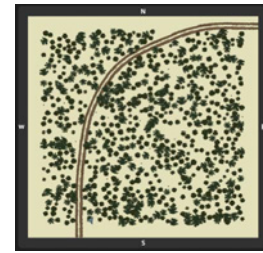
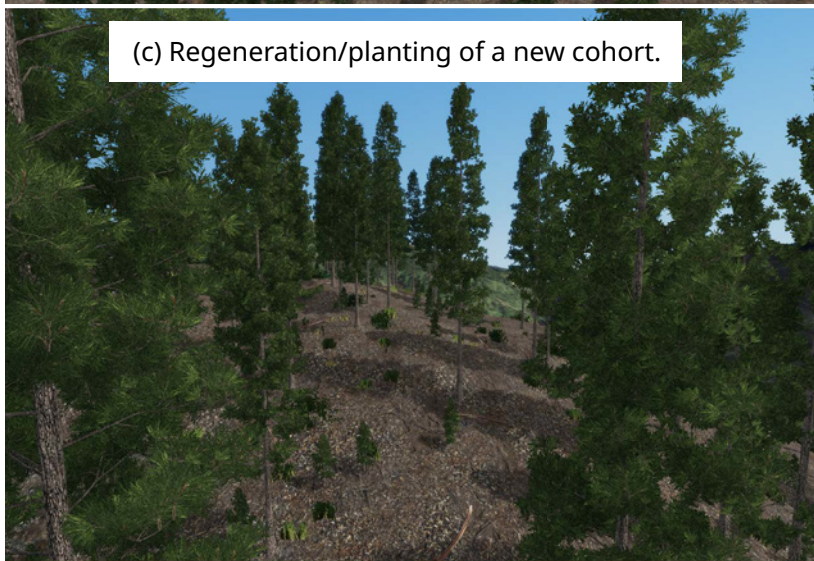
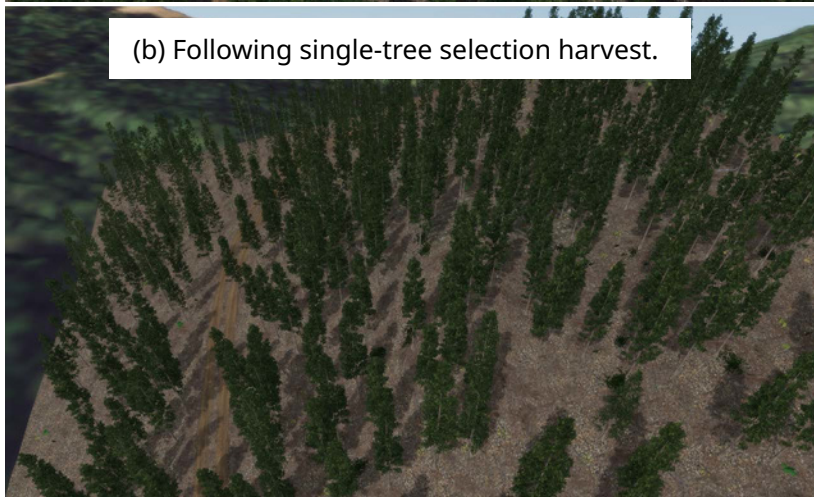
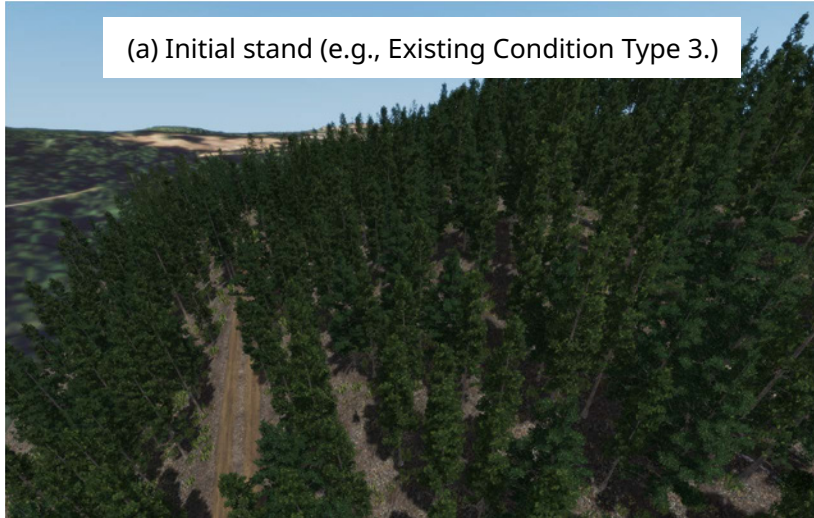
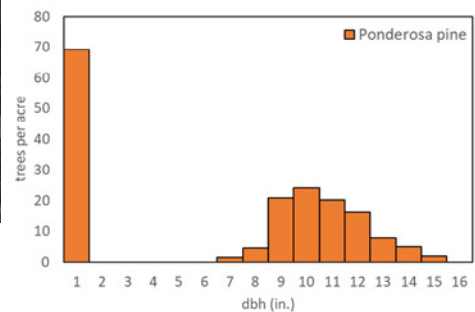
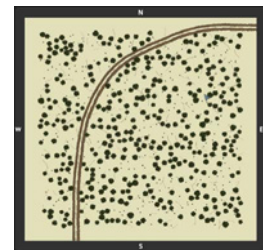


Figure 6.3—A stand on a *Pseudotsuga menziesii* habitat type series that has been treated with a single-tree selection harvest, with pictures before harvest (a), after harvest (b) and after regeneration of a new cohort (c), and planimetric views and example diameter distributions before harvest and after regeneration of a new cohort. In this example, a mechanical vegetation treatment was also implemented to remove the cohort of (mostly) Douglas-fir that was initially present in the understory.



Group Selection

What Is It?

Group selection harvests create growing space for new cohorts by harvesting groups of trees to produce gaps of varying shape and size, distributed throughout the stand. Gap size is conventionally no larger than an area within which surrounding overstory trees exert some environmental influence – approximately two mature tree heights.

Regeneration Mechanism

- Germination and establishment of seed in the created gaps.
- Release of advanced regeneration that established in gaps before harvesting.
- Compatible with planting to expedite and/or increase control over the recruitment process.

Utility in Transformation to Multi-Aged Structure in Ponderosa Pine Stands

In the northern Rocky Mountains, group selection has greater flexibility across a range of habitat types and existing species compositions than single-tree selection. Larger gaps provide sufficient light for the establishment and regeneration of ponderosa pine. These gaps increase the competitiveness of pine, relative to its more shade-tolerant associates, on sites in the *Pseudotsuga menziesii* and *Abies grandis* habitat type series. Through time, repeated group selection harvests can produce stands containing four or more age classes.

Gaps created during regeneration harvest can help with fire hazard management. Gaps, especially larger gaps (for example, ≥ 0.5 ac), break up the continuity of aerial fuels and focusing regeneration on gaps reduces the development of vertical fuel ladders. These horizontal and vertical fuel discontinuities can be further increased by creating and reinforcing persistent mosaic meadows during group selection harvest. Careful selection of the location of these openings can maximize their hazard mitigation potential. For example, knowledge of topographic controls on fire spread can be used to situate openings that slow crown fire spread, and/or to protect denser patches of vegetation retained in an unharvested state for wildlife purposes.

Group selection has practical advantages over single-tree selection that make it an attractive entry point to multi-aged management. Planning and implementing timber harvest under the group selection system can be simpler than in single-tree selection. Regeneration harvests are focused on fewer patches within the stand, and the risk of damage to residual growing stock is lower. Also, marking may be streamlined, although this is dependent on the method of regulating growing stock.

Limitations

- Dense ponderosa pine regeneration in gaps can increase fire hazard. On unproductive sites in particular, growth of seedlings and saplings in these dense clumps may stagnate.
- On sites with abundant herb or shrub cover, resource competition after gaps are created may reduce the density or growth rates of conifer seedlings,
- Even with large gaps, shaded edge conditions may provide favorable microsites for ponderosa's more shade-tolerant associates, especially on less-exposed sites.
- Creation of larger gaps in which ponderosa pine is more competitive may temporarily reduce aesthetic values and the site protection benefits of multi-aged structures.

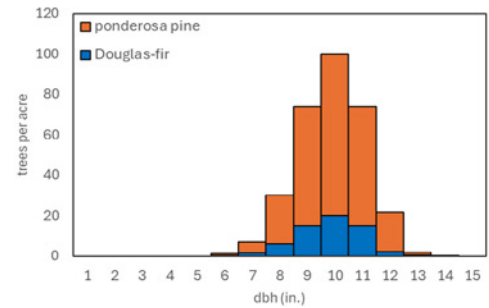
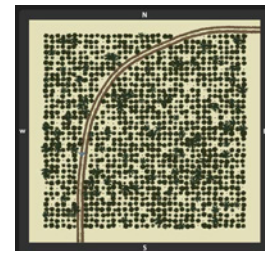
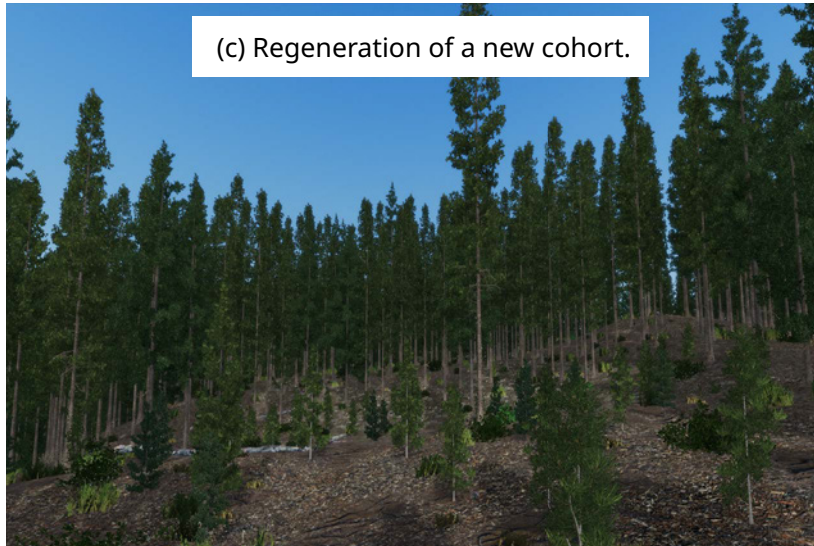
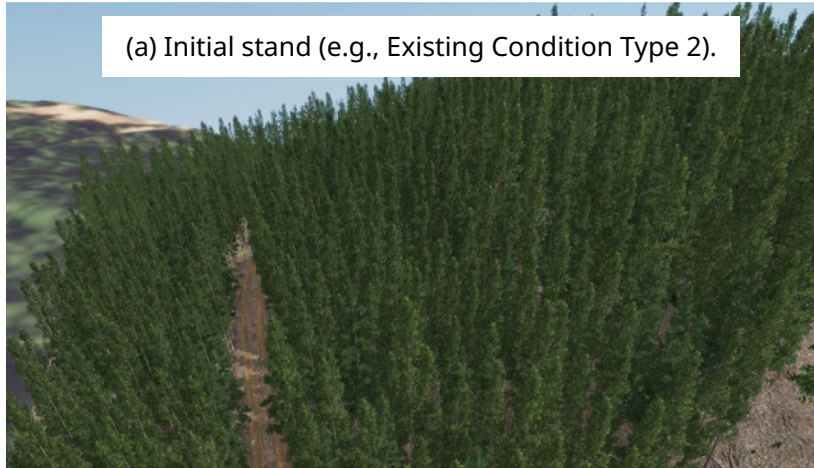
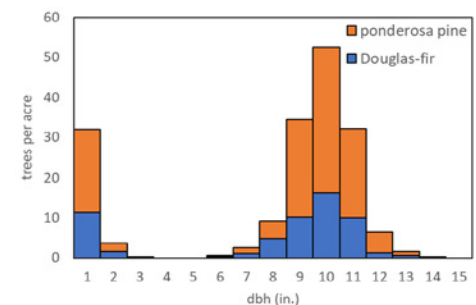


Figure 6.4—A stand on a *Pseudotsuga menziesii* habitat type series that has been treated with a group selection harvest, with pictures before harvest (a), after harvest (b) and after regeneration of a new cohort (c), and planimetric views and example diameter distributions before harvest and after regeneration of a new cohort. In this example, harvesting retained a proportion of Douglas-fir to provide species diversity. Retention of vigorous pine in gaps aids seed dispersal without greatly reducing light availability.



Free Selection

What Is It?

Free selection is a flexible multi-aged practice that may combine elements of any multi-aged and even-aged regeneration harvests at scales ranging from stands to groups of stands (managed in aggregate). More than just a harvest practice, free selection is an approach implemented using a guiding vision statement that encompasses management objectives; it is a theme that describes the stand attributes that will achieve the management objectives and desired future condition (see Graham and Jain 2005 for a thorough discussion and examples). Often, the vision uses qualitative descriptions more than rigid quantitative targets. Free selection encourages recognition of the diverse array of forest structural components and the processes that will maintain these structures through time. Free selection typically produces complex structures suited to varied resource management goals.

Regeneration Mechanism

- Germination and establishment of seed in newly created openings,
- Release of advanced regeneration established before harvesting, and
- Is compatible with planting to expedite and/or increase control over the recruitment process.

Utility in Transformation to Multi-Aged Structure in Ponderosa Pine Stands

Free selection is theoretically extremely well suited to transformation sequences because of its inherent flexibility. The flexibility to combine even-aged and multi-aged treatments across a single site or adjacent stands means that free selection harvests can be implemented in stands with widely varying initial species composition and structure, on all habitat types in which ponderosa pine occurs, and on sites with widely varying physical characteristics.

Free selection harvests are particularly suited to the following circumstances:

- Producing desired future conditions that involve a high degree of spatial complexity in stand structure,
- As the first regeneration harvest in the transformation of stands with a highly irregular structure and/or complex species mix, and
- As mid-transformation treatments in stands where prior treatments produced unexpected and undesirable results, i.e., as a flexible course-correction for treatment sequences that depart from the intended structural path, or in response to non-stand-replacing disturbances.

Although free selection harvests can be implemented as one-off regeneration harvests outside a free selection silvicultural system, the free selection system's emphasis on a qualitative description of desired future conditions helps avoid some challenges associated with free-selection harvesting (below).

Limitations

- Combining multiple regeneration harvest practices within a single stand is counter to standard operating norms, and it presents challenges to the quantitative projection of future stand development.
- Marking a free selection harvest is relatively complicated and requires a high degree of communication with marking crews to convey desired outcomes.
- Unlikely to be suitable where timber production is the dominant management objective due to complications in projecting future harvest volumes and an emphasis on ecological complexity.

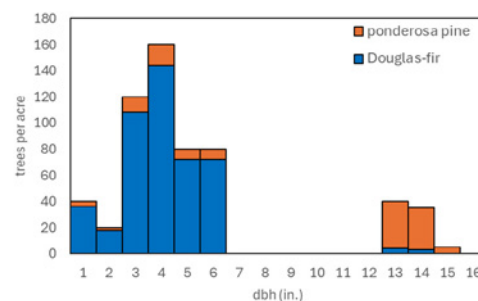
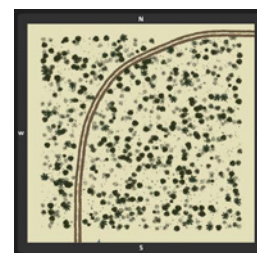
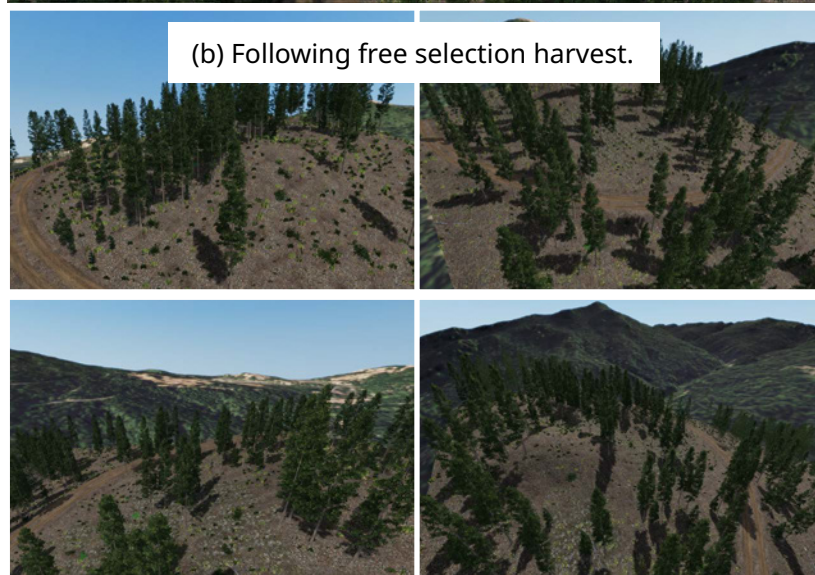
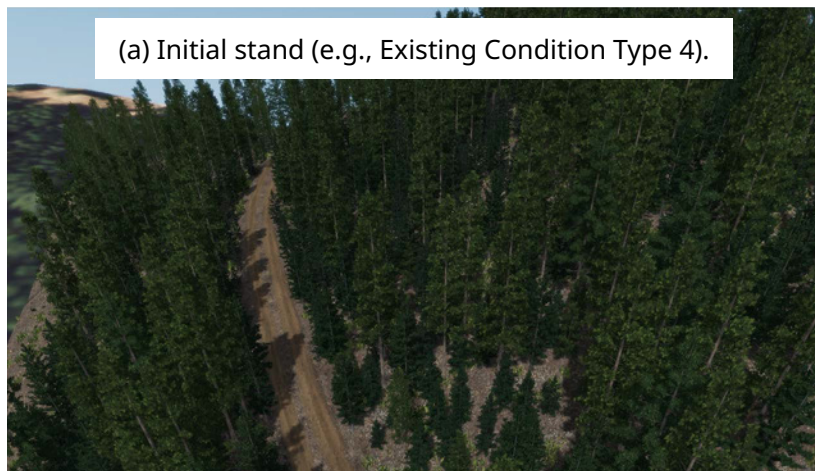
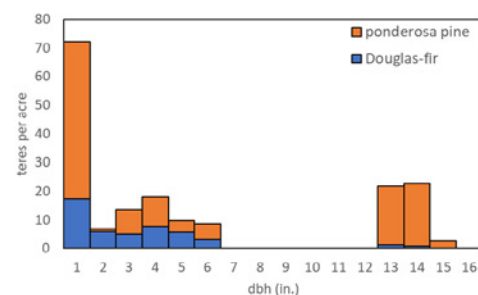
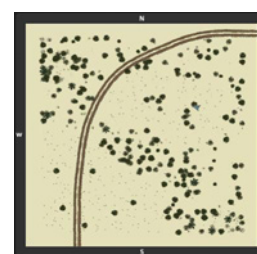


Figure 6.5—A stand on a *Pseudotsuga menziesii* habitat type series that has been treated with a free selection harvest, with pictures before harvest (a), after harvest (b) and after regeneration of a new cohort (c), and planimetric views and example diameter distributions before harvest and after regeneration of a new cohort. In this example, harvest treatments in parts of the stand resemble single-tree and group selection, and seed-tree with reserves.



Irregular Shelterwood

What Is It?

Multi-aged application of the irregular shelterwood involves one or more sequential overstory harvests that establish a new cohort (as with a conventional two- or three-stage shelterwood) while retaining the overwood for more than 20 percent of the rotation and potentially in perpetuity. The resultant stand is often (although not necessarily) two-aged, but may contain three or more cohorts separated by < 20 % rotation age. The irregular shelterwood is an extremely flexible harvest method, providing options for both aggregated and dispersed retention. It also provides a wide range of options for how the overwood remaining after the first shelterwood harvest is managed at the end of the next cutting cycle. Raymond et al. (2009) describe a classification of irregular shelterwood variants; this text has become an essential reference for this silvicultural system.

Regeneration Mechanism

- Release of advanced regeneration.
- Germination and establishment of regeneration seeding in following harvest.
- Compatible with planting to expedite and increase control over the recruitment process.

Utility in Transformation to Multi-Aged Structure in Ponderosa Pine Stands

The irregular shelterwood is highly suited to silvicultural transformation in ponderosa pine because of its flexibility, although ponderosa's low shade tolerance places some limits on the amount and spatial configuration of retained overstory during shelterwood harvests. Site and stand characteristics are likely to determine the number of steps required during the shelterwood harvest. In many situations, multi-stage harvests that progressively reduce the overwood will be required to maintain appropriate light conditions for growth of the younger cohort.

Where the desired future condition for the transformation is a two-aged stand, the entire transformation process may be accomplished over one or two cutting cycles using irregular shelterwood harvests plus intermediate treatments. In other situations, an irregular shelterwood harvest may also be useful as the first step in transformation to more complex uneven-aged structures.

The spatial pattern of overstory retention during harvests should be selected based on the desired future structure and associated management objectives, site characteristics, and the initial stand structure and composition. For example, the presence of a substantial shade-tolerant component in the existing overstory may call for aggregated retention that creates relatively large openings to increase ponderosa's competitiveness relative to other species.

Limitations

- Implementing an irregular shelterwood harvest (especially with dispersed retention patterns) in a stand with shade-tolerant advanced regeneration may be unwise without initial removal of this understory, even if ponderosa pine dominates the overstory.
- Ponderosa pine's low shade tolerance imposes more restrictions on the design of irregular shelterwood harvests than when this treatment is implemented in forests where desired species are shade-tolerant.
- As with conventional shelterwood harvests, dispersed retention patterns increase vulnerability to windthrow in the overwood.

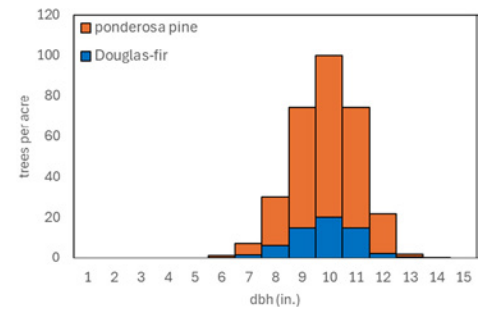
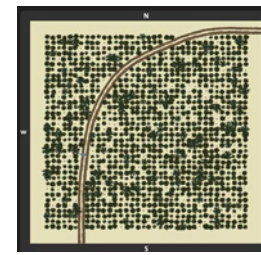
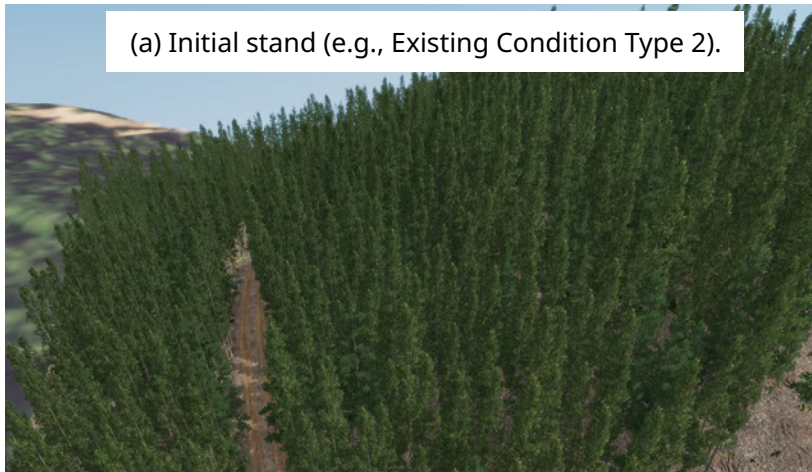
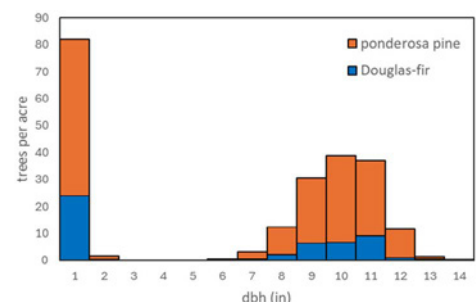
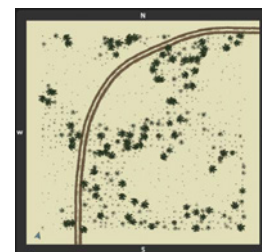


Figure 6.6—A stand on a *Pseudotsuga menziesii* habitat type series that has been treated with an aggregated irregular shelterwood harvest, with pictures before harvest (a), after harvest (b) and after regeneration of a new cohort (c), and planimetric views and example diameter distributions before harvest and after regeneration of a new cohort. In this example, shelterwood harvest did not remove Douglas-fir outside harvest gaps, and this has resulted in the regeneration of some Douglas-fir alongside pine in harvest gaps.



Variable Retention Harvest

What Is It?

Variable retention harvest (VRH) involves the retention of a portion of the overstory cohort for at least a full rotation (and often as perpetual reserves) and is typically conducted in mid-successional stands. Two important characteristics of VRH that differentiate it from the irregular shelterwood are the intent behind structural retention and the types of structures that are emphasized for retention. In VRH, structures associated with mature forests (referred to as biological legacies) are often primarily retained for the purpose of providing continuity of structure and ecological function (e.g., habitat) into the post-harvest community. Because of this framing, VRH emphasizes the retention of structures that include but are not limited to live mature trees¹. For example, some level of snag and down wood retention (or creation during harvest) is a common feature of VRH, as is preserving pockets of undisturbed understory communities using aggregated retention patterns. Variable retention harvest is increasingly recognized as a way of creating an extended period of ecologically complex, early seral habitat to support associated wildlife. Variable retention harvest provides a high degree of flexibility over the type, amount and spatial arrangement (dispersed and/or aggregated) of retained structures. In British Columbia, where VRH is extensively practiced and systematized, the amount and distribution of retention must result in at least 50 percent of the harvest unit being environmentally influenced by mature forest (Beese et al. 2019).

Regeneration Mechanism

- Release of advanced regeneration.
- Germination and establishment of seed produced by retained trees and the surrounding forest.
- Compatible with planting to expedite and increase control over the recruitment process.

Utility in Transformation to Multi-Aged Structure in Ponderosa Pine Stands

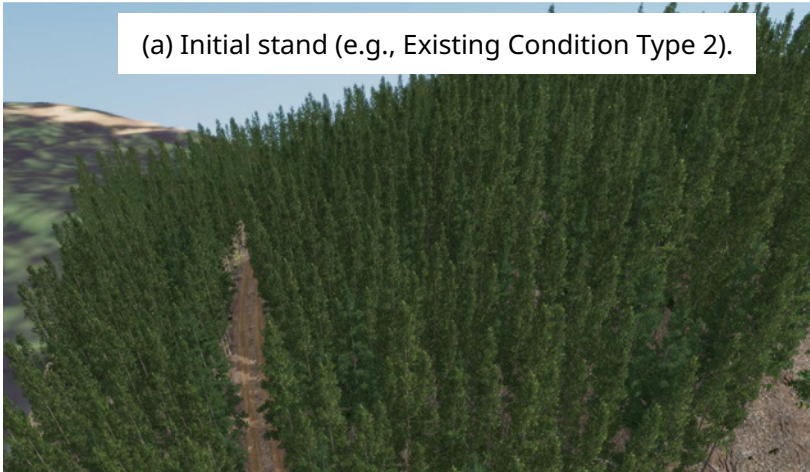
Like the irregular shelterwood, VRH is particularly applicable to transformation to, and maintenance of a two-aged structure, and the first step of transformation to a more complex uneven-aged structure. Repeated VRH with retention of multiple cohorts of overstory trees is possible, but we are not aware of any examples. Similar applications of VRH exist as described for the irregular shelterwood, but the additional emphasis on retention of structures other than live trees makes this practice more suited to objectives associated with wildlife habitat provision. For similar reasons, VRH is also extremely well suited to restoration-oriented objectives involving the creation of stand structures comparable with presettlement ponderosa pine forests. In this, and many other applications of VRH in ponderosa pine forests, the amount of overstory retention will typically be lower than in other forest types.

Limitations

- As with the irregular shelterwood, dispersed retention patterns in mixed-species stands will increase the likelihood of recruitment of shade-tolerant species.
- Marking may be relatively challenging because of VRH's flexibility, the inclusion of dead wood and non-tree structures, and the emphasis on ecological functions of retained structures.
- Larger openings created by aggregated retention may reduce some benefits of multi-aged silviculture, including potential superficial visual resemblance to clearcutting.

¹ These trees provide a lifeboating function for wildlife associated with mature forest, as well as supply seed and ameliorate the soil-surface microclimate.

(a) Initial stand (e.g., Existing Condition Type 2).



(b) Following variable retention harvest.



(c) Regeneration/planting of a new cohort.

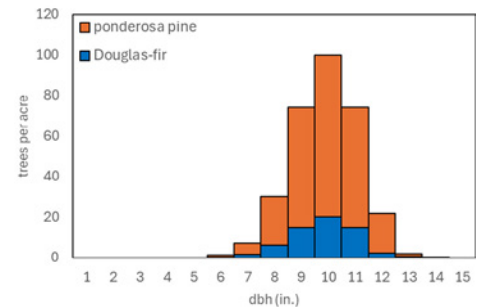
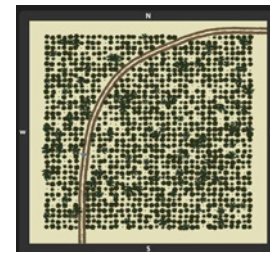
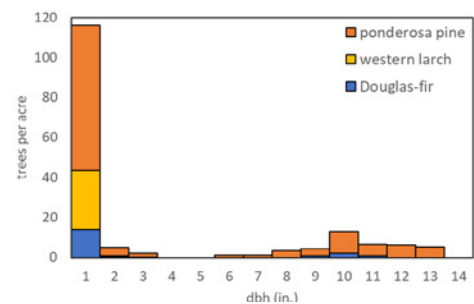
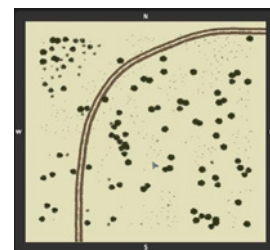


Figure 6.7—A stand on a *Pseudotsuga menziesii* habitat type series that has been treated with a variable retention harvest, with pictures before harvest (a), after harvest (b) and after regeneration of a new cohort (c), and planimetric views and example diameter distributions before harvest and after regeneration of a new cohort. Here, the retention harvest creates one large aggregate, many smaller clumps and lots of dispersed individuals. In this example, planting has been used to add western larch to the species mix.



Hybrid Methods

We distinguish hybrid methods as those in which treatment clearly facilitates regeneration of a new cohort by virtue of creating new growing space, but the immediate intent of treatment is modifying the structure of the existing stand. Each of the regeneration harvest methods described in the previous section promote regeneration while incorporating some degree of intentional change in the growing environment of residual trees and/or a desirable change in stand structure (relative to management objectives). However, in these harvest methods, regeneration of a new cohort is the primary treatment intent. Intermediate treatments, on the other hand, have the intent of modifying residual tree vigor and resource availability or altering stand structure after the period of cohort establishment. Hybrid treatments share this emphasis on modifying existing stand structure and residual tree competitive status, but in so doing these changes create significant growing space for new cohort establishment. The latter component may be an implicit assumption of treatment implementation—as is the case in some restoration treatments (e.g., fig. 6.8)—or may be a more explicit aim—as is the case with current applications of variable density thinning (Palik and D’Amato 2023).



Figure 6.8—This stand on the Boise Basin Experimental Forest (U.S. Forest Service, Rocky Mountain Research Station) in central Idaho displays low overstory density, heterogeneous tree spacing and a mixture of openings, individual trees and tree clumps following a restoration treatment.

Variable Density Thinning

What Is It?

Variable density thinning (VDT) is a harvest method in which harvest intensity (proportion of trees removed) is varied across the stand to increase horizontal and vertical heterogeneity. This emphasis on post-treatment heterogeneity has given rise to the primary application of VDT, to date: to accelerate the development of complexity in simplified, young to early mature stands, such as plantations. In its simplest—and original—form VDT may prescribe variable residual spacing throughout the stand (e.g., crop-tree release). However, the current iteration of VDT (Palik et al. 2020) involves (1) retaining patches of untouched forest (termed *skips*), (2) creating gaps, and (3) thinning the forest between skips and gaps (*matrix thinning*) to varying levels of residual basal area and tree spacing. Gap creation in these current VDT practices serves an important primary function of diversifying within-stand horizontal structure. These gaps also create conditions that facilitate seedling establishment and/or release. This regeneration component is not consistent with conventional use of the term thinning. Variable density thinning is therefore a hybrid method.

Regeneration Mechanism

- Germination and establishment of seed from surrounding trees in lower density matrix thinning or in created gaps.
- Release of advanced regeneration.
- Planting in gaps is commonly used to expedite and increase control over regeneration.

Utility in Transformation to Multi-Aged Structure in Ponderosa Pine Stands

Variable density thinning is particularly applicable to the transformation of young plantations that have limited existing structural complexity (for example, existing condition Type 1). In these situations, VDT may be the initial regeneration harvest in a transformation sequence, serving to increase within-stand variability, while enhancing growth rates of trees in the matrix and providing opportunities to regenerate (naturally or planted) a new cohort in gaps. In mixtures of ponderosa pine and Douglas-fir or grand fir, the matrix thinning component of a VDT harvest can be used to reduce the density of the more shade-tolerant species, thereby serving a stand improvement function.

Its inherent flexibility makes VDT a relevant tool for a wide range of site and habitat types. As stands age during the transformation sequence, repeated VDT harvests can be used to produce structurally complex uneven-aged stands. As with group selection harvests, the gaps created during a VDT harvest may serve multiple purposes, including fire-hazard reduction. Making use of the latter property will be particularly important if skips are incorporated into the VDT treatment, as these represent pockets of elevated fire hazard. Therefore, effective VDT treatment in ponderosa pine stands will require careful consideration of skip and gap placement.

Limitations

- Tracking the location of skips and gaps becomes increasingly challenging when VDT is used repeatedly.
- In mixed species stands, skips that contain shade-tolerant species will supply seed to promote recruitment of these species.
- Marking a VDT treatment can be relatively complex and benefits from an understanding of the underlying ecological basis to maximize potential multi-objective benefits.

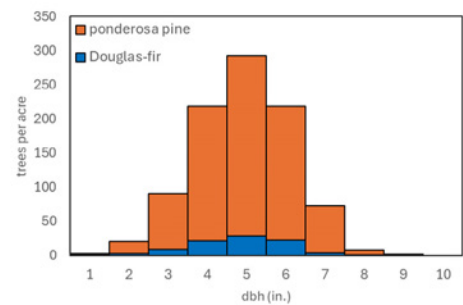
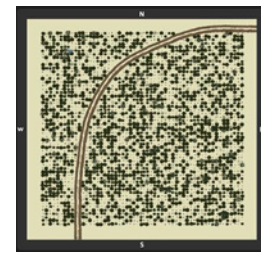
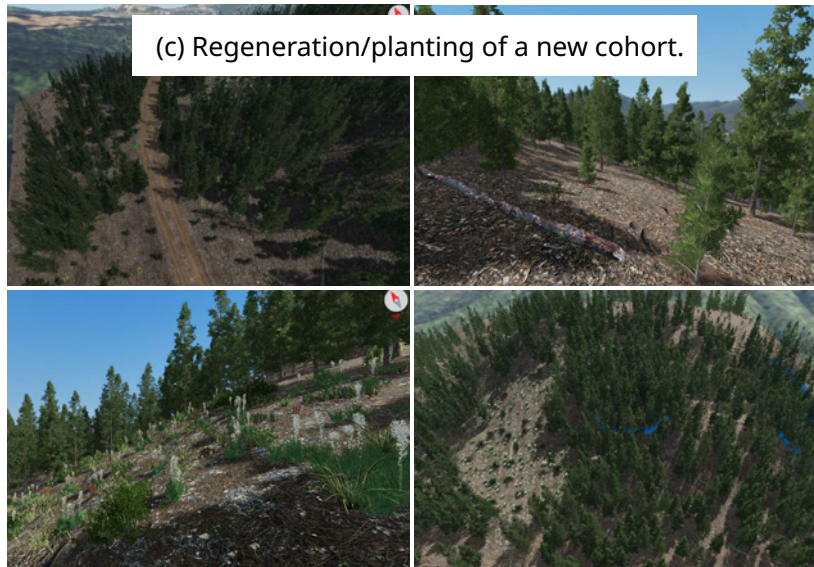
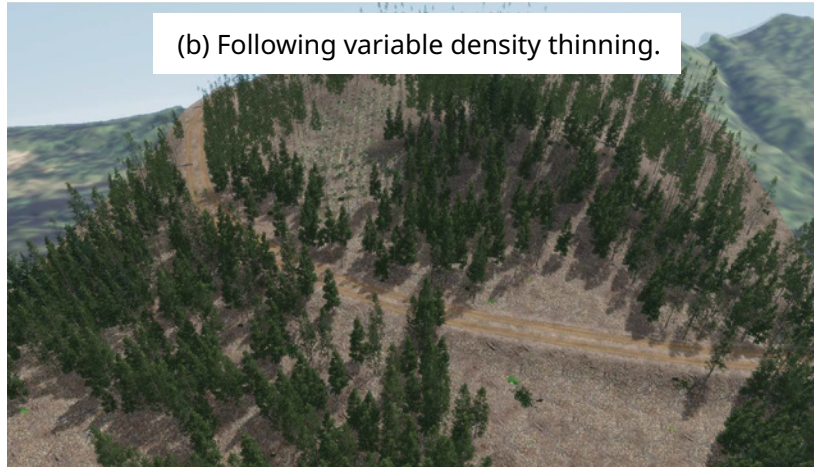
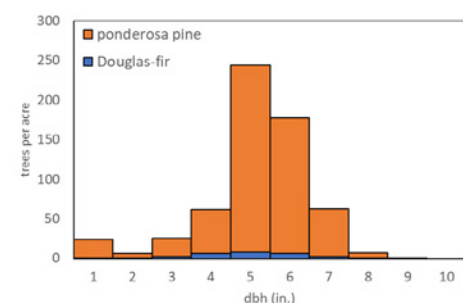
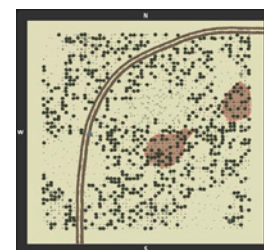


Figure 6.9—A stand on a *Pseudotsuga menziesii* habitat type series that has been treated with a VDT harvest, with pictures before harvest (a), after harvest (b) and after regeneration of a new cohort (c), and planimetric views and example diameter distributions before harvest and after regeneration of a new cohort. In this case, VDT has created four gaps, with one maintained as an open mosaic-meadow (c, lower left) to promote understory plant diversity. Skips were also created (two of which are highlighted in red on the planimetric image and blue in image (c) lower right).



Restoration Treatments

What are They?

Restoration treatments have traditionally emphasized returning stand structure and composition toward structures found in pre-Euro-American settlement forests. Dendroecological reconstructions of presettlement era stand structure are commonly used as the reference conditions for designing these restoration treatments. However, the complexity and degree of specificity of these structural targets varies considerably. More recently, restoration applications have also attempted to identify structures that are consistent with the core elements of pre-settlement forest structure and are also adapted to projected changes in climate and disturbance regimes for the target site. Examples of restoration treatments vary in the extent to which management objectives other than structural restoration guide treatment design, and this may influence which structures are prioritized. For example, restoration treatments in ponderosa pine forests may emphasize creation of wildlife habitat (Long and Smith 2000; Youtz et al. 2008).

Utility in Transformation to Multi-Aged Structure in Ponderosa Pine Stands

Restoration treatments may be useful (but limited) tools for silvicultural transformation. One use of restoration treatments is in unmanaged ponderosa pine stands that have an overstory of presettlement age, but have infilled with shade-tolerant species (e.g., existing condition Type 5). In these stands, achieving the range of desired future conditions may primarily involve a restoration treatment that removes or reduces the density of younger cohorts (often of shade-tolerant species) that have developed following fire exclusion.

Restoration treatments also provide the initial template for overstory tree density and distribution in young plantations and mid-successional stands where an important management objective is development of the structures, processes, functions, and resilience associated with the natural model of stand development. In these situations, a restoration treatment may be the first stage in a transformation sequence. Implicit in the restoration treatment (and its classification as a hybrid method in this guide) is the idea that growing space created during treatment will provide opportunities for regenerating cohorts. However, restoration treatments and the reference conditions on which they are based do not directly consider the requirements for regeneration, such as opening sizes and seed source. Implementing a restoration treatment in a young stand must be accompanied by the considerations and practices that will ensure adequate regeneration.

Reference conditions have been developed for many ponderosa pine forests in and beyond the northern Rocky Mountains (e.g., Clyatt et al. 2026; Fiedler et al. 2007). An increasingly common approach for operationalizing these reference conditions is the ICO method for marking and quantifying spatial patterns (box 5).

Limitations

- Many published examples of reference conditions are either too vague or too complex to be directly inserted into silvicultural prescriptions (hence the value of ICO-type methods).
- Restoration treatments typically provide a static structural blueprint that is not sufficiently grounded in stand dynamics to serve as a silvicultural prescription or a system of management.

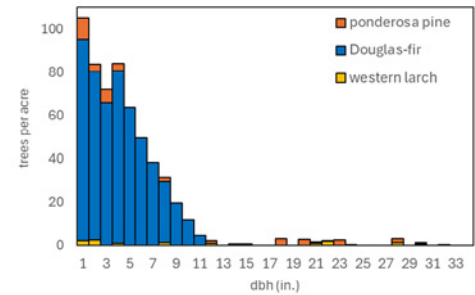
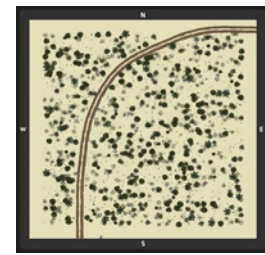
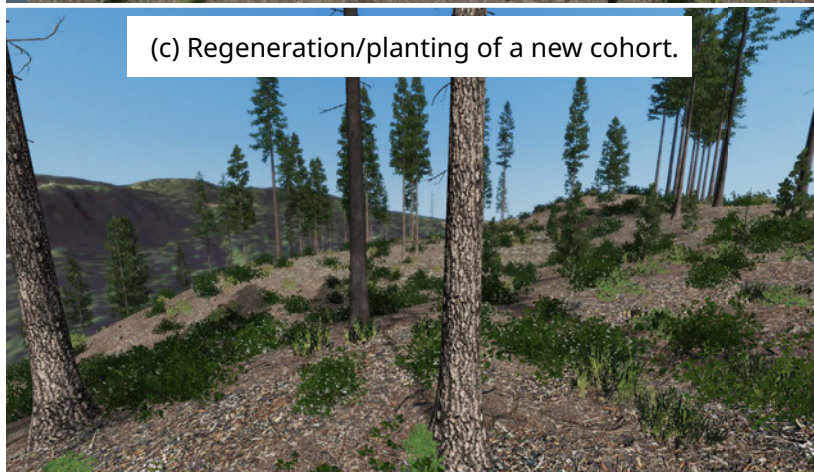
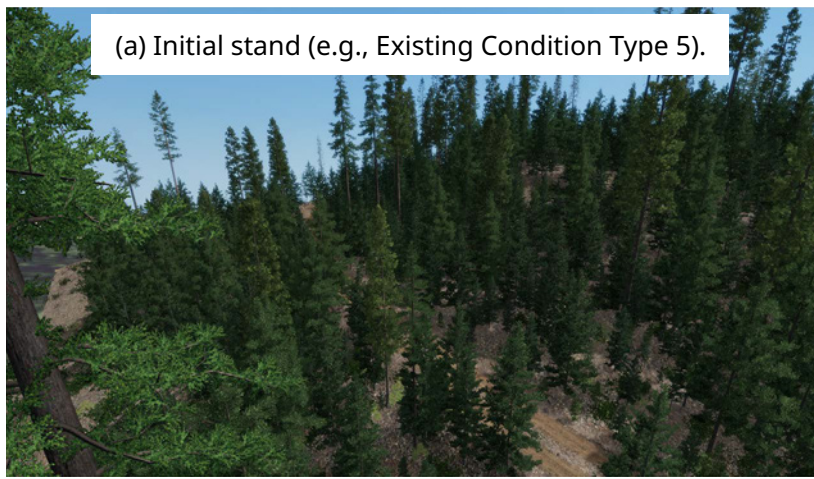
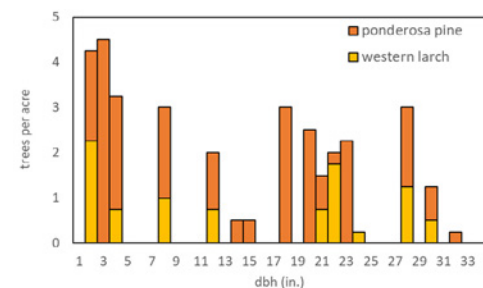
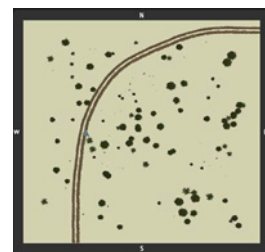


Figure 6.10—A stand on a *Pseudotsuga menziesii* habitat type series that has been treated with a restoration treatment, with pictures before harvest (a), after harvest (b) and after regeneration of a new cohort (c), and planimetric views and example diameter distributions before harvest and after regeneration of a new cohort. Restoration harvest has created a structure with varied tree spacing, and clump sizes. In this example, regeneration of a new cohort has occurred in the growing space created by the restoration treatment.



Box 5 - Individuals, Clumps, and Openings (ICO)

What Is It?

The ICO approach is a stand-scale tool for creating and monitoring spatial heterogeneity (Churchill et al. 2013, 2016) that is most often used to generate marking guides for commercial harvests or non-commercial biomass removal. Although the ICO approach is rooted in ecological science (Larson and Churchill 2008, 2012), it is an operational method developed for efficiency and ease of implementation (Churchill et al. 2016) and is now available as an Android-based app for use in the field (Maher et al. 2019). To date, ICO methods have been most widely used as a tool for generating the spatial template used in marking forest restoration treatments, primarily (although not exclusively) in western dry forests, including ponderosa pine and dry mixed-conifer. Other potential applications exist within the realm of multi-aged silviculture; ICO marking could be used directly as part of treatments other than restoration, and the methods and concepts of ICO could be modified or augmented to incorporate other structural or functional information.

Ecological Underpinnings

The foundation of the ICO approach is the clump and gap spatial structure that is visible, in various forms, in many western forests that have an intact disturbance regime. This structure is commonly found in reconstructions of pre-fire suppression era forest structure (e.g. Arno et al. 1995). This structure, which developed under the influence of low- to moderate-severity fire, is composed of a mosaic of individual trees, tree clumps of varying sizes (i.e., variation in the number of trees per clump), and openings of various sizes and shapes. This spatial pattern and the processes that maintained it provided the different ecosystem functions associated with these forests, such as a species-rich herbaceous understory that provides abundant forage (Churchill et al. 2017; Larson and Churchill 2012). This spatial pattern is also thought to be essential to the resilience of forests to many disturbance and climate change stressors (e.g., Hessburg et al. 2019). The ICO method translates this spatially heterogeneous mosaic into quantitative targets to guide marking or monitoring.

Implementation

Unlike many marking approaches that use basal area, ICO provides targets that are stated in terms of the number of trees to be retained, the sizes of the clumps of retained trees and the proportion of the total number of trees in each clump size. For example, what proportion of the retained trees should be individual trees, small clumps of trees (e.g., 2–5 trees), medium clumps, and large clumps? An assumption of ICO marking is that small openings are created when clumps are marked. However, experience implementing ICO marking suggests that large openings (> 0.5 acre) and skips require intentional marking. Another central tenet of ICO implementation is that targets for tree density, clump sizes, and proportions of trees in each clump size apply at the scale of harvest units, rather than on each acre, which encourages variability in marking across the unit. Toward this last objective, targets may be expressed as ranges.

The targets used in ICO marking guides have typically been developed from reconstructions of stand structure pre-Euro-American settlement. Generating these reference spatial patterns from stand reconstructions is seldom feasible for practitioners, but reference patterns have already been developed for selected sites in the northern Rocky Mountain region and elsewhere (e.g., Churchill et al. 2017; Clyatt et al. 2016).

Reconstructing pre-settlement stand structure is not the only method of generating reference spatial patterns for ICO targets, although these reconstructions may provide a useful initial building block for making modifications. Expert opinion, experience in the forest, and some ecological understanding of how stand spatial structure relates to site characteristics through the processes of stand development and disturbances can also be valuable aids in developing ICO targets.

A reference spatial pattern generated from another site should never be lifted and used as a template for ICO marking without considering its fit with the characteristics and management objectives of the site and target stand. Site characteristics, such as habitat type, topography, soils, existing stand structure, and management objectives, should influence the ICO targets for the site. Potential changes in climate on the site may also warrant consideration. These changes may alter resource availability and the capacity of the site to sustain a spatial arrangement similar to that which existed several centuries ago.

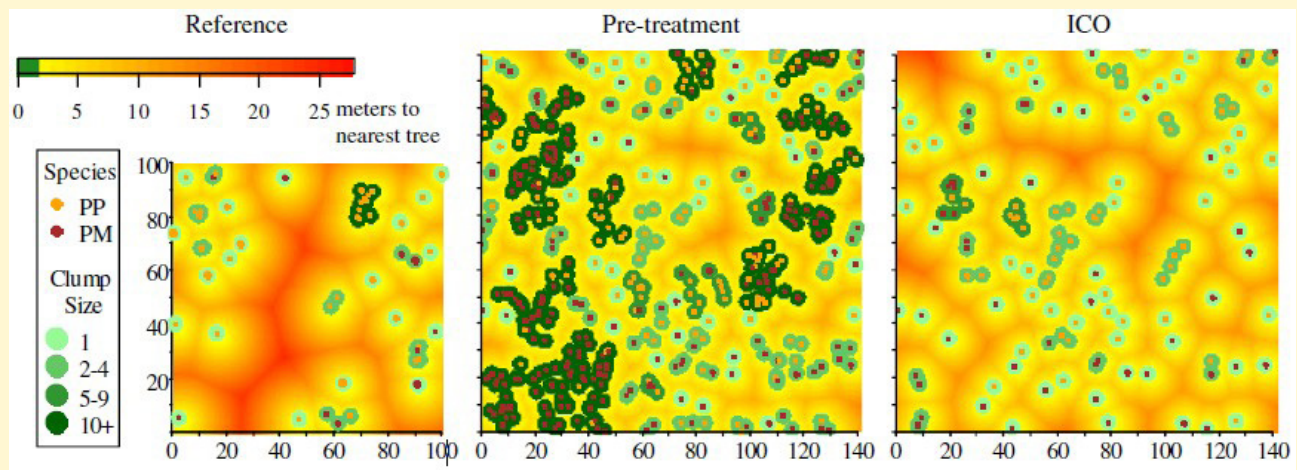


Figure 6.11—An example stem map showing tree spatial pattern and distances from nearest trees in a reference stand (left), and a target stand before (middle) and after (right) a restoration treatment using an ICO marking guide. Trees are displayed as points (PP = ponderosa pine, PM = Douglas-fir) surrounded by a colored ring denoting clump size using different shades of green. Distances from the nearest tree clumps are displayed as the yellow to red color ramp. All distances are in meters. Reference conditions and the treated stand are located in the Eastern Cascades of Washington. Courtesy image by Churchill and others, 2013, used with permission.

Application in silvicultural transformation and multi-aged silvicultural systems

The immediate focus of the ICO approach is on spatial patterns, not on aspects of stand dynamics necessary for the continuation of a multi-aged stand. It is important to be aware of this when considering the potential role of ICO methods in silvicultural transformation and multi-aged silvicultural systems. In particular, recruitment of new cohorts and the need to create conditions for regeneration are not explicitly accounted for in ICO marking guides. As discussed below, it is possible to broaden this focus.

The most direct application of the ICO approach is marking restoration treatments, intermediate harvests, and noncommercial treatments. A diverse spatial structure is an important prescription objective for the residual stand. When used in thinning treatments (both commercial and precommercial) in stands with limited existing heterogeneity, ICO can help diversify stand structure. The resulting stand structures may reduce fire hazard while also enhancing broader ecological functions and aesthetic values of the stand. This is often not the case in a standard spacing-based fire hazard reduction thinning.

When used in marking a variable density thinning treatment, ICO can set the initial spatial structure, while reducing stand density to increase tree vigor and reduce disturbance risks (Churchill 2021). Like ICO, variable density thinning has a goal of increasing spatial heterogeneity. Therefore, ICO methods are particularly well suited to stands in Existing Condition Types 1 (young plantations) or 2 (mid-seral plantations).



Figure 6.12—Openings, and individuals and small clumps of ponderosa pine and Douglas-fir are evident in this image from a stand containing large, old trees pre-dating Euro-American settlement, located in the Bitterroot Valley of western Montana. Charred bark from past surface fires is visible on trees in the foreground.

A broader interpretation of the role of ICO methods is in regeneration harvests, especially single-tree and group selection (Churchill et al. 2016). The ICO approach does not necessarily consider tree size, form, or other criteria of interest for determining suitable seed sources, wind hazard, wildlife habitat potential, and so on. Likewise, its emphasis on spatial pattern does not explicitly consider gap size requirements for competitive regeneration of target species (ponderosa pine in this case). Both elements could be incorporated into a modified ICO marking guide to increase the utility of this method in multi-aged silvicultural prescriptions.

When used in marking selection harvests, pairing ICO methods with one of the less rigid forms of stocking control discussed later in this chapter is more realistic than integration with, for example, BDq stocking control. This is not to say that the ICO approach could not be combined with a relatively rigid target diameter distribution, but doing so would almost certainly be time-consuming and require a very experienced marking crew. More realistic is to pair ICO methods with stocking control based on individual tree assessment for retention. This would use general marking principles for selecting suitable residual growing stock in dry-mixed conifer forests (e.g., Churchill 2021; Powell 2018). In practice, this process could operate by first identifying a cadre of vigorous trees of any size (if they exist). These trees will serve as wind-firm, future seed sources and would be used as the basis for building out the ICO spatial template. When used this way, ICO becomes a formalized process for generating the *clumpy-gappy* structure that is often recommended in ecologically-based selection harvests in ponderosa pine forests (e.g., Fiedler 1996; Fiedler and Cully 1995).

Ensuring that opening sizes meet the regeneration requirements of ponderosa pine (and western larch, depending on the site) is likely to depend on (1) appropriate matching of the ICO spatial pattern to site and existing stand characteristics and (2) achieving sufficient variability in ICO implementation across the harvest unit. The ICO marking guides developed from historical stand reconstructions in sites with a major ponderosa presence should implicitly provide conditions that enabled regeneration of ponderosa pine on that site under an active fire regime. This does not imply that regeneration occurred in a timeframe consistent with current silvicultural guidance or norms for satisfying other management objectives. If relatively long post-harvest regeneration periods are tolerable, gap sizes from an ICO marking will probably be adequate for ponderosa pine regeneration.

On sites in the *Pseudotsuga menziesii* and *Abies grandis* habitat type series, competition from species with a higher shade tolerance than ponderosa pine, which could prevent pine dominance, is a related concern. Where either Douglas-fir and/or grand fir are major components of the existing overstory, ICO marking patterns are likely to be subsidiary, if used at all, to the requirement of prioritizing retention of all ponderosa pine (Churchill 2021; Churchill et al. 2017). Where ponderosa is the major component of a mixed stand, ICO marking guides will need to accommodate the preferential removal of the non-pine species and the creation of enough moderate to large (> 0.25 acre) gaps that favor ponderosa pine regeneration. The location of these larger gaps can be mapped out before marking the stand (Churchill et al. 2017). One way to ensure that some suitable conditions exist for ponderosa pine regeneration is by having high variability in the ICO clump-size targets and openings across the stand. This high variability will ensure that at least some openings are large enough for ponderosa pine to have a competitive advantage, even if it has a disadvantage in smaller openings. These highly variable spatial patterns are thought to have been common at the moister end of sites supporting ponderosa pine in the *Pseudotsuga menziesii* and *Abies grandis* habitat type series (Churchill et al. 2017).

What Happens Next? Long-term Management Using ICO Methods

The potential value of ICO marking over the longer term in stands that have been harvested using an ICO marking (i.e., second-entry ICO) has received little research attention. We are not aware of any examples of this in practice (ICO methods were introduced relatively recently). Could repeated commercial thinnings in a two-aged stand, repeated variable density thinning entries, or repeated selection harvests be marked using ICO methods? If so, would these entries be designed to reinforce the initial spatial pattern or nudge the spatial template in different directions?

In ponderosa pine stands with an intact disturbance regime, fire was a critical regulatory force behind the ICO structure, but other factors were also influential (Hessburg et al. 2015; Larson and Churchill 2012). The interaction of these factors with regeneration patterns and growth leaned toward maintenance of a consistent pattern of clumps and openings on some sites. On other sites, clumps and openings were more dynamic. If the cutting cycles in a managed multi-aged stand are sufficiently long relative to site productivity, managers should have opportunities to modify clump sizes, locations, and openings using ICO methods over subsequent entries. A similar range of ICO targets could be used in re-entries. However, the ICO approach may be more valuable as a way to monitor stand development through time, relative to a target spatial pattern. In this scenario, the locations of clumps and openings created during the first entry could form a starting point for retention, reduction, or expansion of clumps based on recruitment, growth, and natural mortality since the last harvest.

Summary

The ICO approach can be used to develop a template for marking guides and is a way to monitor spatial pattern in forest stands. It has been used in operational settings, mainly for restoration, but there is still much to learn about its implementation, performance, and potential uses in a multi-aged silvicultural system.

Intermediate Treatments

Intermediate treatments can play an important role in silvicultural transformation to multi-aged structure in ponderosa pine stands. While regeneration harvests create growing space for recruiting new cohorts to form the multi-aged structure, intermediate treatments, such as thinning, can facilitate successful, future regeneration harvests by focusing growth on desirable species and individual trees likely to provide good cone crops. Intermediate treatments also contribute to stocking control, improving or maintaining stand vigor, and achieving specific target structures. The next section reviews the basics and potential utility of common intermediate treatments for silvicultural transformation in ponderosa pine stands.



Figure 6.13—A mid-successional ponderosa pine-dominated stand in northern Montana that has been managed using repeated thinning (with recent understory mastication).

Commercial and Precommercial Thinning

What Are They?

These cultural treatments are implemented to focus site resources on specific species, size classes, or numbers of residual trees, to enhance forest health, and/or to recover potential economic value that would otherwise be lost as mortality. Commercial thinning removes trees of merchantable size, while precommercial thinning (PCT or noncommercial) reduces density in sub-merchantable size classes. Differences in thinning methods and their application may produce a wide range of residual structures ranging from uniform to heterogenous, each suited to different management objectives.

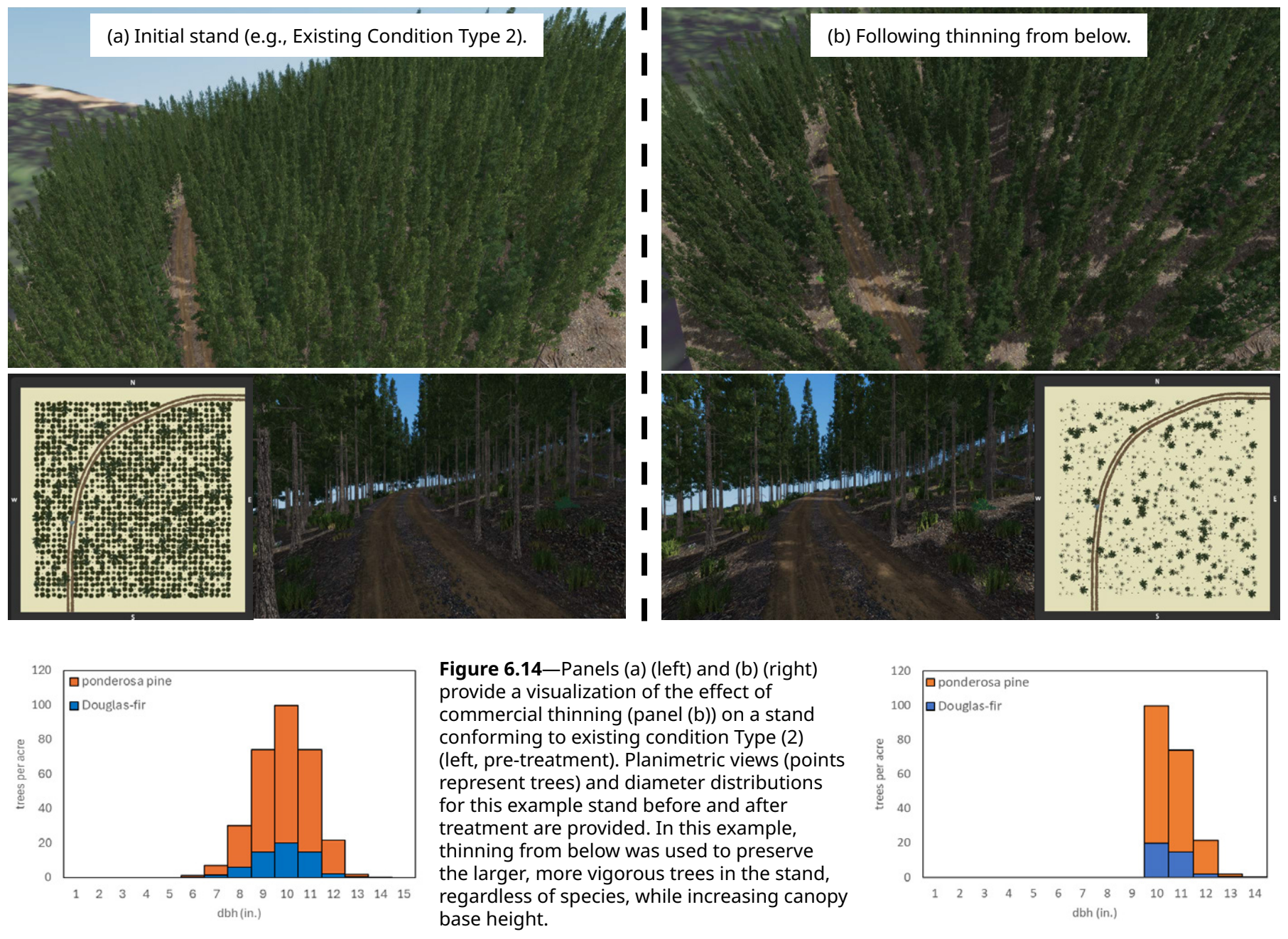
Utility in Transformation to Multi-Aged Structure in Ponderosa Pine Stands

Commercial thinning and PCT are extremely useful intermediate treatments during transformation. In most cases, thinning can contribute to multiple objectives, including increasing growth rates of preferred species and size classes and reducing vulnerability of residual trees to drought, insects, and fungal pathogens. Thinning is particularly effective in ponderosa pine, which has the capacity to release following stand density reduction in trees of all age and size classes. Examples of the potential use of thinning in silvicultural transformation of ponderosa pine stands include:

- On sites in the ponderosa pine series, implementing thinning as the first step in the transformation of dense young stands serves to (1) increase growth of residual growing stock (which also serve as future seed sources) and (2) create enough growing space around the residual trees to permit subsequent single-tree selection harvest. Absent this initial thinning, gaps created by single-tree selection in dense, young stands may be too small to promote ponderosa pine recruitment.
- Integrating commercial thinning or PCT into group and free selection harvests provides an efficient means of controlling stocking in the matrix around harvested groups.
- Precommercial thinning is useful for regulating the density of new cohorts regenerating in gaps and other openings created during regeneration harvest. In two-aged stands (such as those produced through irregular shelterwood or variable retention harvest), PCT and commercial thinning can be similarly used to control the density of the younger cohort as these trees age, but before subsequent regeneration harvests.
- In overstocked two-aged stands containing an older pre-settlement cohort, thinning the younger cohort may be the first step in a transformation sequence.

Limitations

- As with any harvest practices that do not use whole-tree harvesting (to reduce fuel accumulation) or are not followed by prescribed burning (to consume fuels), activity fuels generated by thinning will temporarily increase fire hazard. Similarly, opening the canopy during any harvest will raise surface temperatures and windspeeds, so may increase fire hazard. This effect may be pronounced following geometric, evenly-spaced thinning treatments that homogenize surface conditions with fewer shaded tree clumps.
- Most common thinning methods (e.g., thinning from below or above designed to increase vigor or reduce aerial fuels) homogenize stand structure by reducing crown class variability. The common-practice of removing dead and dying stems during thinning also has negative consequences for wildlife dependent on these structural features. These drawbacks can be reduced by using free thinning that retains some suppressed and dead trees.



Prescribed Fire

What Is It?

Prescribed fire is any fire intentionally ignited or used by management in accordance with applicable laws, policies, and regulations to meet specific objectives. Numerous parameters of the burn can be adjusted to modulate fire behavior and effects according to management objectives. Prescribed burns are typically relatively low-intensity treatments used to reduce activity fuels following harvest, control competing vegetation, and expose mineral soil to promote conifer regeneration. Much less common, higher intensity fires may be used as a regeneration method and to increase landscape heterogeneity (box 6).

Utility in Transformation to Multi-Aged Structure in Ponderosa Pine Stands

Prescribed fire is relevant to silvicultural transformation and subsequent long-term management on most sites through its role in fuel reduction pre- and post-harvest, in understory density management, and in seedbed preparation. Examples of the role of prescribed fire in a transformation context include:

- Prescribed fire alone or soon after a mechanical treatment may be the first step in the transformation of stands containing advanced regeneration of shade-tolerant species. In these stands, conducting a regeneration harvest without underburning (or mechanical equivalent) after harvest is likely to result in an understory dominated by shade-tolerant species, even if ponderosa pine dominates the overstory. Periodic reapplication of prescribed fire at the time of regeneration harvest may be required to control further shade-tolerant regeneration.
- Low-intensity prescribed fire can be used in harvest gaps and openings to thin dense clumps of regeneration. This helps to prevent stagnation of the new cohort.
- On sites in the *Pseudotsuga menziesii* or *Abies grandis* habitat type series, use of prescribed fire when the regenerating cohort is of sapling size should favor ponderosa pine over its more shade-tolerant associates, which have a marked fire-tolerance deficit at this size.
- Broadcast burning is an important means of reducing activity fuels produced by harvesting at any point during transformation. Application of prescribed fire after harvesting also improves seedbed conditions for ponderosa pine and western larch, which have a stronger preference for mineral soil and ash seedbeds than associated shade-tolerant species.
- Prescribed fire is a vital structural maintenance tool after transformation of the stand to the desired multi-aged condition when it can be used repeatedly following or independent of harvesting. Prescribed fire is a key maintenance tool on sites where restoration of pre-settlement structure is the primary management objective and timber harvest or mechanical understory treatments are not desirable for various reasons. Here, repeated burning is among the only means of preventing the build-up of excessively dense understory and midstory vegetation.

Limitations

- Limited burn windows, personnel and, in the wildland-urban interface, social license.
- First-entry application of prescribed fire in many stands containing remnant pre-settlement trees surrounded by younger in-fill exposes the older cohort to mortality risk caused by substantial duff accumulation around tree bases and abundant ladder fuels.
- Fuel treatment effectiveness diminishes through time, requiring repeated treatment. For dry, low-elevation ponderosa pine forests, the effective duration is likely to be one

to three decades. Shorter timeframes can be expected on sites where fuels accumulate more rapidly (e.g., areas with favorable micro-climatic conditions).

- Successful application of prescribed burning in multi-aged stands benefits from horizontal separation of cohorts of different ages and sizes (i.e., situations in which younger trees are growing underneath or adjacent to older trees). This may be especially difficult to achieve in stands managed using single-tree selection, because it requires an extremely well-targeted burn application. Mastication is an alternative (box 7) to prescribed burning for fuel reduction but has trade-offs for short-term fuel profiles and fire hazard. These trade-offs can be minimized by treatment design and implementation.
- It can be difficult to use prescribed fire to thin regeneration and reduce ladder fuels if trees have grown to a size where fire intense enough to be lethal would also cause undesirable levels of mortality of larger trees (Greenler et al. 2023).

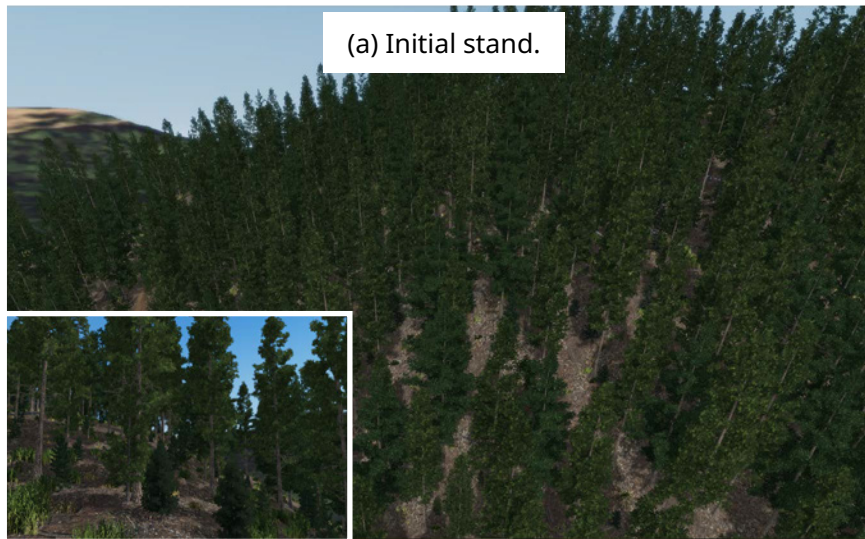
Box 6—Prescribed Fire as a Regeneration Method

Prescribed fire is almost always used to (1) reduce understory and ladder fuels, (2) reduce understory conifer density as part of stocking control, and/or (3) in site preparation. These uses involve low to moderately low-intensity fire. Higher intensity prescribed fire may also have value as an integrated regeneration method (i.e., creating growing space by killing overstory trees and preparing the seedbed). Fire is not typically used in this capacity because it is a blunt tool for killing overstory trees, even when there are differences in fire tolerance among overstory species (Greenler et al. 2023). Risks of fire escaping control lines are also higher than is typically tolerable, especially in areas adjacent to the wildland urban interface.

Perhaps the most obvious circumstance for the use of prescribed fire as a regeneration method is in designated wilderness. In these locations, mechanical harvesting is not permitted, but prescribed burning is allowed in certain cases. Prescribed fire in wilderness may have value in achieving multiple objectives, including reducing overstory density and creating seedbed conditions to help develop more complex, resilient multi-aged stand structures. Other sites that are far from human populations are also potential candidates. This is especially true in areas with poor road networks, on steep terrain that renders ground- or cable-based logging systems infeasible, and where timber values do not justify helicopter logging. On these sites, using fire to achieve regeneration objectives and shift stand structure toward the range of desired future conditions could be combined into landscape-scale pyrosilviculture (North et al. 2021; York et al. 2021).

To date, most applications of high-intensity prescribed fire have been conducted at the meso-scale rather than as smaller stand-scale operations. In the northern Rocky Mountains, high-intensity prescribed burns have been used in lodgepole pine and mixed-conifer forest types (Hood, in press), primarily in mountainous terrain. In such topographically complex terrain, spatial variability in fuel moisture increases the likelihood of variable burn severity, which serves to increase landscape heterogeneity. As with lower-intensity prescribed fire, adjusting the season of burning favors different levels and continuity of overstory mortality to suit differing management objectives. Comparisons can also be drawn with published examples of wildfire serving restoration objectives by selectively killing overstory and midstory trees (Kane et al. 2019; Larson et al. 2013) and the increasingly prevalent use of managed wildfire for restoration purposes (Barros et al. 2018; Huffman et al. 2020).

While the use of high-intensity prescribed fire in stand-scale treatment programs is relatively untested, we include it here because of its undoubted value in the silvicultural toolbox; practitioners may evaluate the practice according to their risk tolerances for target stands.



(a) Initial stand.



(b) Following irregular shelterwood harvest.

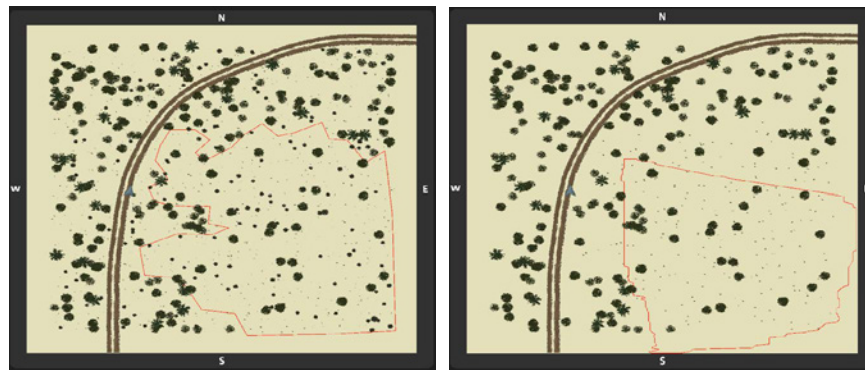
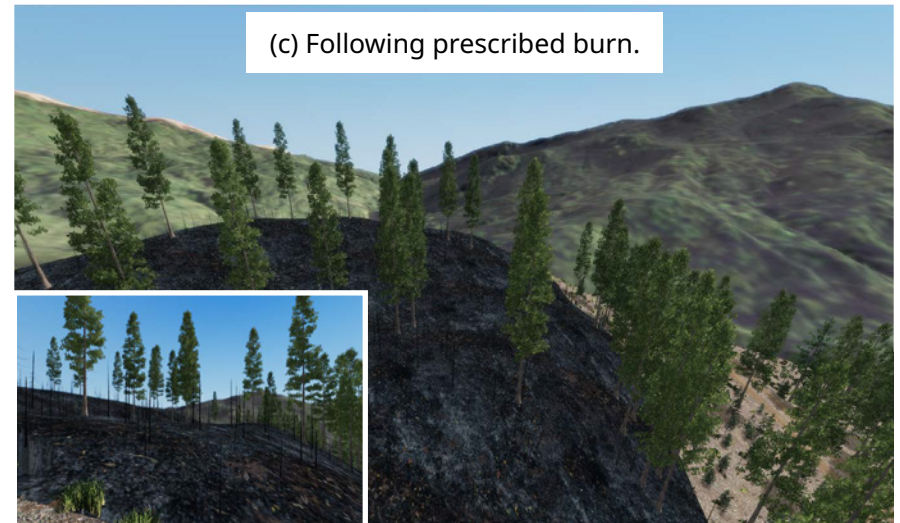


Figure 6.15—Visualizations above and right provide an example of the use of prescribed fire (c) in a mature stand (a) to kill a shade-tolerant understory layer after first reducing overstory density with an irregular shelterwood harvest (blue polygon) (b). Planimetric views, immediately above, highlight the area of shelterwood harvest (red polygon, left image) and subsequent prescribed burn (red polygon, right image).



(c) Following prescribed burn.

Box 7 – Mastication as a Vegetation Management Tool

Mastication is a form of mechanical understory vegetation management in which shrubs, saplings, small trees and/or dead wood (typically material with diameter < 8 inches) are converted into small chips, shreds and chunks that are typically left in the forest (Jain et al., 2012, 2018). Equipment used for mastication includes ground-mounted horizontal drums and boom-mounted rotating drums, and is typically limited to slopes < 30 percent. Mastication has most commonly been used as a fuel treatment, as an alternative to prescribed fire. Used in this capacity, mastication typically converts ladder fuels into surface fuels and alters the size and surface area:volume ratio of the material. This has implications for fire behavior (e.g., flame length, residence time) and ecological effects (e.g., soil burning, canopy consumption/scorching) in the event of a fire that must be carefully considered. Jain et al. (2012) provide a more detailed review of the advantages and disadvantages of mastication versus prescribed fire for achieving fuel goals.

Although rearranging fuels may be an important rationale for using mastication during transformation to and perpetuation of multi-aged structure, mastication can also be conceived more broadly as a tool for controlling stocking and manipulating species composition to promote and maintain ponderosa pine dominance. Examples of this include mastication of a Douglas-fir and grand fir-dominated understory beneath a predominantly pine-dominated overstory after regeneration harvest. Additionally, certain types of equipment, especially boom-mounted mastication heads, have demonstrated sufficient flexibility and accuracy to enable relatively finessed removal/retention of saplings and small trees based on species in mixed understories (fig. 6.16).

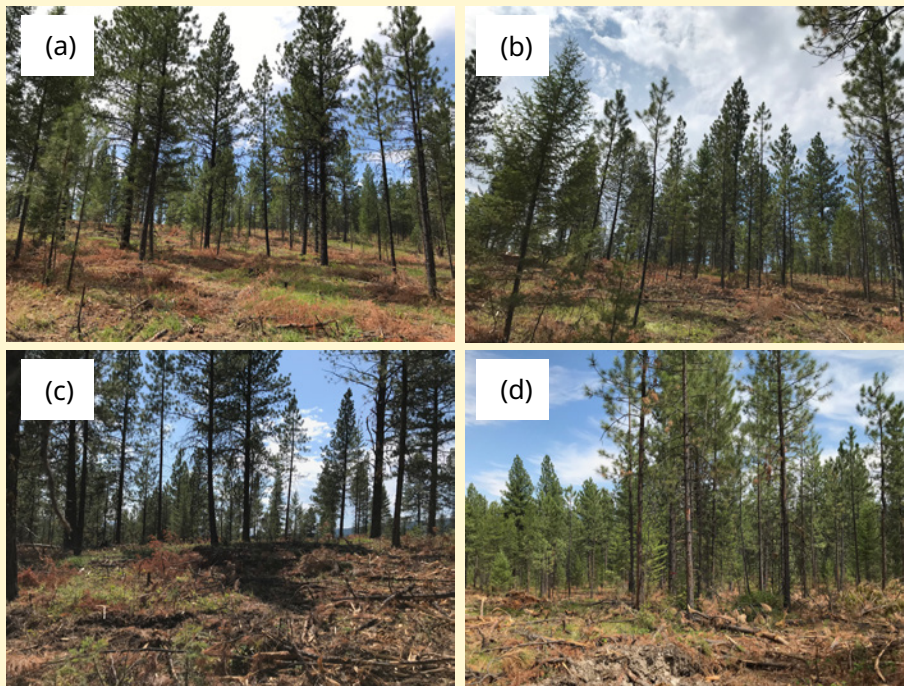


Figure 6.16—The understory of a repeatedly thinned stand that was recently masticated to reduce ladder fuel accumulation but retain a proportion of pre-existing saplings and understory trees, with a preference for ponderosa pine retention, to promote a multi-aged structure. A boom-mounted, rotating-disk masticator was used in this treatment. Images show the variability in fuelbed conditions and surface fuel sizes that may be created by mastication, as well as the heterogeneity in understory structure that may be produced using this form of treatment. This stand is located on the Lubrecht Experimental Forest in western Montana.

Stand Improvement Treatments

What Is It?

Improvement cutting is the removal of less desirable trees of any species in a stand of pole-sized or larger trees, primarily to improve composition and quality.

Utility in Transformation to Multi-Aged Structure in Ponderosa Pine Stands

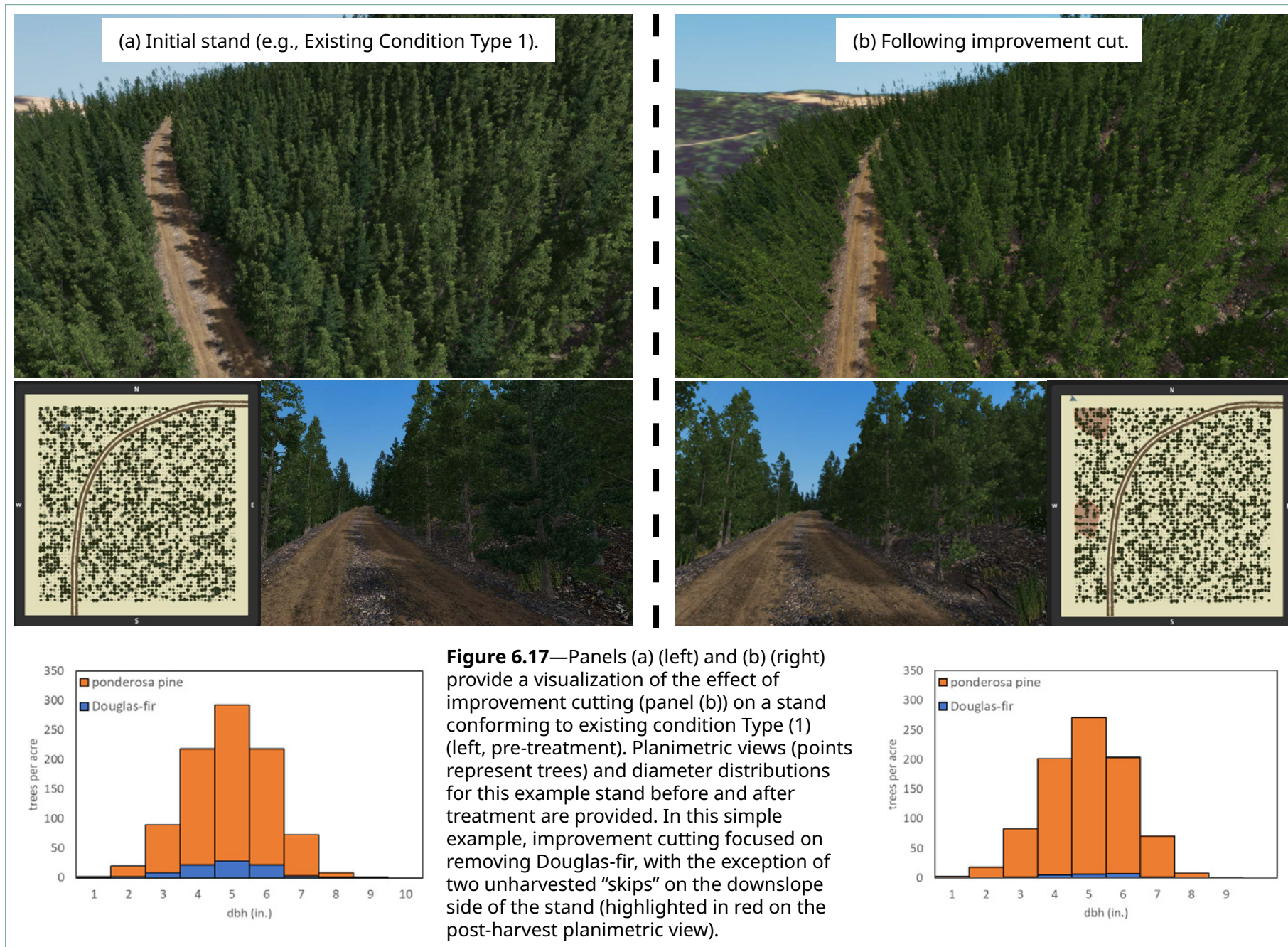
Improvement cutting is particularly relevant to the transformation of stands in which the overstory includes modest to intermediate proportions of Douglas-fir or grand fir in addition to ponderosa pine. In such stands, improvement cutting to favor ponderosa pine, combined with prioritizing the removal of shade-tolerant species during regeneration harvest, can help ensure that the next cohort of seedlings is pine-dominated.

Improvement cutting of the form described above can be integrated into thinning treatments designed to achieve other objectives or combined with a regeneration harvest (chapter 8). Often, improvement cutting will be most useful as an initial step in a transformation sequence by creating the conditions for a successful regeneration harvest. Improvement cutting may also occur at later stages in the transformation process to adjust the species composition of any cohort. This may be especially useful as a course correction when regeneration harvests designed to favor ponderosa pine unintentionally promote Douglas-fir or grand fir.

On ponderosa pine habitat types, thinning treatments with an improvement cutting component may still be useful for shifting residual overstory toward vigorous trees likely to provide good seed crops and those most likely to be windfirm. The relevance of such treatments depends on site conditions and the extent to which these outcomes can instead be achieved during regeneration harvests.

Limitations

- As with thinning, exercise care during improvement cutting to avoid negative consequences for ecosystem function and diversity. Taken to the extreme, improvement cutting that removes all non-ponderosa pine and/or trees with low vigor, poor form, or crown structures likely to be susceptible to wind-throw (e.g., *wolf trees*) can have adverse effects on biodiversity and reduce the nutrient inputs that would follow from mortality of low-vigor individuals. In most circumstances, improvement cutting can achieve the primary objectives while also retaining a minor proportion of less desirable trees that perform important ecological functions. The effects on understory composition of retaining a minor proportion of shade-tolerant species in the overstory can be minimized by clustering retained individuals in specific areas of the stand, rather than dispersed throughout the stand.
- Improvement cutting to ensure ponderosa pine dominance may require multiple entries. This may still prove challenging on sites surrounded by mature stands containing a high-proportion of shade-tolerant species, especially on sloping ground and where the target stand has a high edge to area ratio.
- Improvement cutting to remove pole-sized trees is difficult to justify on financial grounds. This limitation may be minimized by integrating improvement cutting into a commercial harvest entry.



Sanitation and Salvage Treatments

What Is It?

Sanitation harvests remove trees to improve stand health by stopping or reducing the actual or anticipated spread of insects and disease. Salvage harvests remove dead trees or trees damaged or dying because of injurious agents other than competition, to recover economic value that would otherwise be lost.

Utility in Transformation to Multi-Aged Structure in Ponderosa Pine Stands

Sanitation and salvage harvests may be incorporated into the transformation process. In most cases, these treatments will be a response to disturbances occurring during transformation, rather than formalized in a predefined transformation sequence. An important exception is where the transformation target stand has an ongoing insect or disease outbreak.

To a significant extent, decisions to implement sanitation or salvage harvests during transformation will be driven by factors other than pure silvicultural merit, including wider ecological objectives, landowner policies and preferences regarding sanitation/salvage cutting, and landscape context. Dead and dying trees created by disturbances are important wildlife habitat and serve many other ecological functions from stand to landscape scales. Silvicultural approaches that seek to promote broad ecological integrity will therefore often avoid high-intensity sanitation or salvage harvests. However, not salvaging large populations of dead or dying trees can also present risks, especially in landscapes already heavily affected by similar disturbances. Sanitation/salvage treatments that retain a proportion of dead or dying trees, rather than all of them, may provide a way of balancing the ecological merits and risks presented by large populations of dead and dying trees.

Because of the complexity of factors influencing the application of sanitation and salvage treatments and the unique characteristics of each stand and disturbance event combination, discussion below is limited to the silvicultural considerations that are immediately relevant to the goal of regenerating new cohorts in the transformation to a multi-aged structure.

- Ponderosa pine (and western larch to an even greater extent) is less vulnerable to most common fungal pathogens than its more shade-tolerant associates, notably Douglas-fir and grand fir. The presence of disease pockets (e.g., a root rot pocket) in these associated species at the start of the transformation process may be used to advantage by conducting a salvage and/or sanitation harvest of some or all affected trees to create an opening(s) for regeneration of a new ponderosa pine cohort. Experimentation with this novel approach on the Lolo National Forest in western Montana (J. Person, personal communication) highlights the importance of ensuring that healthy ponderosa pines dominate the gap edge community to provide seed. One tactic to promote this ponderosa pine dominance is to combine the salvage/sanitation treatment with improvement cutting.
- Dead trees may reduce available light, but they also moderate micro-climatic extremes for vulnerable seedlings on the forest floor, which improves survival rates. This should be accounted for when determining the role and specifications of any salvage/sanitation cutting, especially on steep slopes, south-facing exposures and otherwise harsh sites.
- Cones present in dead and dying trees are an important seed source for recruitment of a new cohort following disturbance. Evaluate the cone crop in dead or dying ponderosa pine before making sanitation/salvage decisions; this information should influence the timing and design of any such treatments.

- Dwarf-mistletoe or Comandra blister rust (*Cronartium comandrae*) infections are examples of pathogens whose presence in the overstory can undermine transformation to multi-aged structures. Infected trees typically develop complex crown structures that have considerable habitat value. Minor dwarf mistletoe infections may not be a major risk to transformation, especially when infected trees are localized rather than dispersed throughout the stand. However, infection of a high proportion of overstory trees is a significant risk to the viability of current and future regeneration. These trees are highly exposed to rust infection and mistletoe seed-rain, which severely compromises the development or maintenance of a multi-aged structure. In such situations, sanitation cutting of most infected trees may be the most efficient and effective transformation path. In this scenario, vigorous uninfected trees should be carefully identified, and these locations should be the immediate focus of sanitation cutting. Cutting should begin as soon as possible to limit infection of the healthy residual growing stock. These uninfected trees will serve as a seed source (potentially supplemented by planting) and will help moderate the soil-surface microclimate for seedlings, provide continuity of mature forest functions while the next cohort regenerates, and form the spatial template for subsequent development of the multi-aged stand.



Figure 6.18—This gap, approximately two acres in size, was originally a pocket of root rot in Douglas-fir, and is one of several gaps in a stand that has begun the process of transformation to multi-aged structure. In this gap, Douglas-fir is the dominant component of the new seedling cohort, likely because of the presence of vigorous, mature Douglas-fir at the gap edge.

Stocking Control in Multi-aged Silviculture

Stocking control is the process of managing site occupancy, including the number, size, species, and spatial arrangement of trees to attain management objectives for the stand (O'Hara and Gersonde 2004). In multi-aged stands, the terms *stocking control* and *growing stock regulation* commonly refer to the process of allocating growing space between the various woody components of the stand (O'Hara 2014). These components may be expressed as cohorts, diameter classes, canopy strata, or many other differentiating factors. The metrics used to quantify the growing space occupied by these different components are equally varied (e.g., basal area, volume, stand density index). Regardless of which components or metrics of growing space occupancy are used, stocking control provides the framework that ensures long-term sustainability of the resource.

During a transformation sequence, allocating sufficient growing space to new cohorts when conducting regeneration harvests and during subsequent intermediate treatments is the most important form of stocking control. Devoting growing space to new cohorts has implications for other components of the stand, notably the overstory in a previously even-aged stand. Decisions about how much growing space to allocate to these other stand components and the spatial arrangement of this allocation, will be required during transformation (fig. 6.19). Other factors may influence this decision, including specific stand structures envisioned in the desired future condition and intermediate management objectives to be satisfied during the transformation process (e.g., ensuring a periodic supply of wood products). The importance of these factors may determine whether one of the more formal methods of stocking control should be used during transformation or whether to use an informal procedure that is primarily focused on a conservative allocation of growing space to new cohorts.

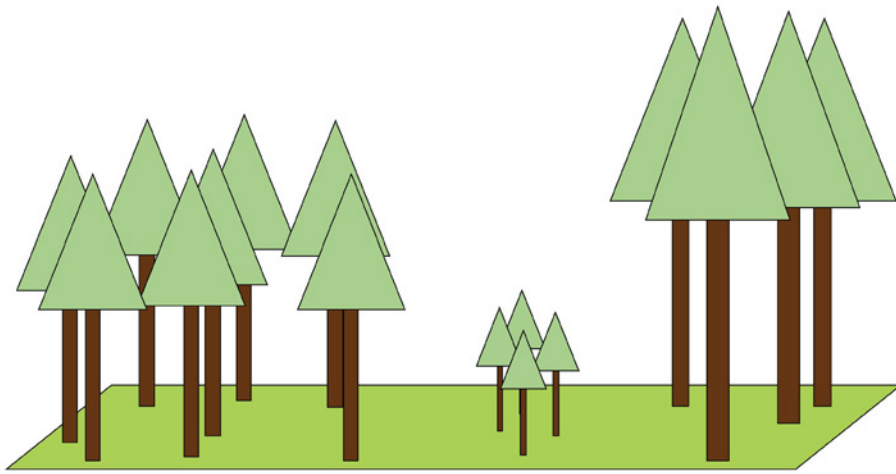
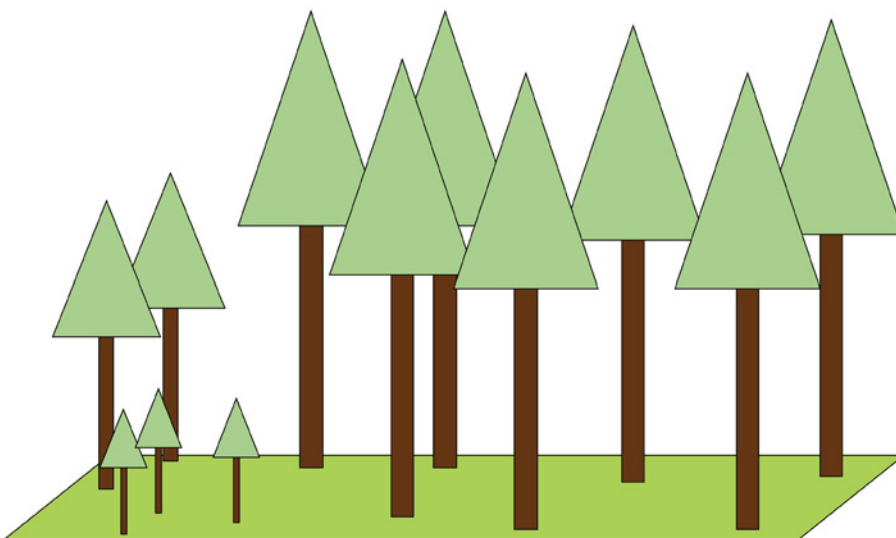
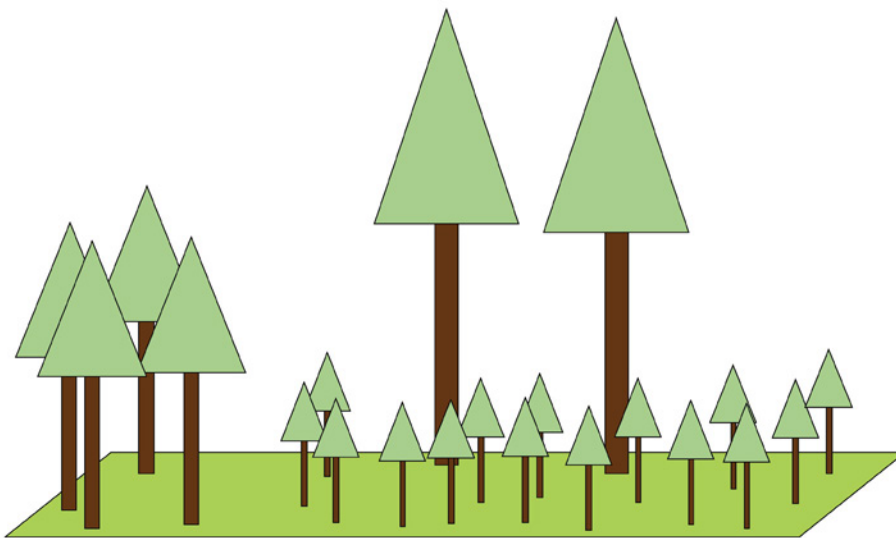


Figure 6.19—Three alternative allocations of growing space between cohorts in a three-cohort stand, each of which may be suited to different desired future conditions, management objectives or site characteristics.



Stocking control is fundamental to sustainable multi-aged management, and its role varies according to management objectives, site and stand characteristics and resource availability. For example, where sustained timber yield is of primary importance, precise regulation of growing stock can ensure consistent volume production through time. If the principal management objective is providing habitat for one or more wildlife species requiring a specific stand structure, then stocking control should seek to maintain (approximately) that structure through time. In many other cases, stocking control may simply consist of ensuring that sufficient regeneration is present to eventually replace overstory trees, when they are harvested or senesce, within a management-relevant timeframe.

Stocking control methods in multi-aged stands vary from relatively complex practices to simple, “light touch” approaches, and from formalized systems to informal “rules of thumb”.

Stocking control methods in multi-aged stands vary from relatively complex practices to simple, light-touch approaches and from formalized systems to informal rules of thumb. In North American forestry literature, the BDq method is perhaps the most widely described stocking control method (e.g., Ashton and Kelty 2018; Leak 1964; Nyland 2016). In some texts, the BDq and related approaches are almost synonymous with selection-based uneven-aged management (Powell 2018). However, uneven-aged management, including single-tree selection, can be practiced without these intensive approaches to stocking control. In fact, in practice, it is likely that a wide range of informal procedures, locally applied and deriving from practitioner familiarity with site and species silvics, are more common than strict adherence to the BDq (O’Hara et al. 2002). The BDq method is best suited to stands that are managed to provide a predictable, stable timber yield (although Seymour and Kenefic 1998 and O’Hara 2014 discuss some flaws in this regard). This situation is not common in ponderosa pine forests on public land. Therefore, while the BDq method certainly has value, including in ponderosa pine stands (e.g., Arno 1999; Fieldler and Cull 1995), it should not be viewed as the default strategy for stocking control in multi-aged ponderosa pine stands.

Below, we describe a spectrum of alternative stocking control approaches, from informal, “light touch” strategies to more complex methods, in order to illustrate the flexibility and breadth of possible options. Descriptions are intended as an overview, with specific points of relevance in ponderosa pine forests, and will not serve as detailed guidance for implementation (see the reference list at the end of this document for useful resources). Practitioners should adopt, modify, or develop a stocking control method that is suited to their local circumstances and that draws on experience-based intuition and knowledge of site and species characteristics.

Regeneration Control

What Is It?

This informal strategy focuses on regeneration density and spatial distribution and is compatible with any multi-aged regeneration harvest method. Stocking control is limited to ensuring that recruitment of target species is sufficient to (1) eventually replace the oldest cohort when it is harvested or senesces and (2) that the spatial distribution of this regeneration is consistent with the management objectives for the stand. Implementation requires identifying a target density of established seedlings or saplings by a specific time after harvest. This regeneration density target should incorporate potential seedling survival rates and mortality over the decades until the cohort reaches maturity. With this target density, a regeneration harvest can be designed and implemented based on existing and desired future structure and site characteristics to create the conditions to achieve the desired level and distribution of seedling recruitment. This approach is also compatible with planting; the regeneration density target should incorporate potential seedling survival rates. Use stocking surveys to assess the success of regeneration outcomes against the target density at the specified post-harvest timeframe.

Developing a target regeneration density to ensure the eventual replacement of the oldest cohort on the site can be as simple or complex as desired, and it can draw heavily on practitioner experience, intuition, and knowledge of site characteristics and their influence on species silvics.

Application in ponderosa pine stands

This technique is applicable to any site or stand characteristics. On sites outside the *Pinus ponderosa* habitat type series where regeneration of less desirable shade-tolerant species is likely, regeneration targets should account for the effect of these less-desirable species on growing space for ponderosa pine.

The flexibility of this approach can be maximized by adopting a more relaxed timeframe for determining regeneration success. Recognize that securing regeneration in unmanaged ponderosa pine stands has historically been a longer process than is desirable when managing for timber production. Applicable *free to grow* or *green-up* regulations may limit flexibility in some circumstances.

Advantages

- Simple design and application.
- No attempt to monitor or control density across diameter classes.
- Extremely flexible.
- Allows for (and benefits from) practitioner intuition and experience with the site and species.

Disadvantages

- The flexibility and absence of a detailed framework for application will not suit all preferences.
- Unsuitable to management objectives requiring specific stand structures or control of many structural components.
- Uncertainty about stand dynamics over short and long timeframes due to the absence of monitoring and control of the diameter distribution.

Individual Tree Evaluation

What Is It?

Also termed *free* stocking control (O'Hara, 2014), this is an informal approach in which the stocking level emerges through a bottom-up process. Retention, removal, or modification of stand structural elements (individual trees, clumps of trees, snags, and so on) are evaluated based on the current and potential future contribution of each element to the desired future condition, stand management objectives, and more general ecological functioning. For live trees, vigor and crown structure are important considerations when evaluating the tree for retention or harvesting. This evaluation process includes consideration of spatial and non-spatial dimensions.

The Stoddard-Neel Approach (SNA) (Mitchell et al. 2006; McIntyre et al. 2008) practiced in the frequent-fire longleaf pine (*Pinus palustris*) forests in the southeastern U.S., is a formalized method of stocking control based on individual tree evaluation. This method is based on the philosophy that no single ecosystem value should be maximized at the expense of others (Palik et al. 2002). In practical terms, the SNA emphasizes maintaining spatial heterogeneity in tree density, retention of large trees, and harvesting only a proportion of gross growth during each cutting cycle. Although some elements of the SNA approach are tailored to the longleaf pine ecosystem, many key tenets and practices could be adopted or adapted to ponderosa pine forests in the northern Rocky Mountains.

Individual tree evaluation is most suited to selection systems (single, group, free), variable retention harvest, and restoration treatments. Experimental implementation of free selection in ponderosa pine forests has used individual tree evaluation because of this approach's flexibility.

Application in Ponderosa Pine Stands

Individual tree evaluation formed the basis of the first documented multi-aged management systems in ponderosa pine forests—the maturity selection and improvement selection systems of Munger 1941 and Pearson 1942, respectively. Individual tree evaluation is most useful in ponderosa pine or mixed species stands that possess some existing structural heterogeneity. The approach is suited to many common management objectives in ponderosa pine forests. This includes fire hazard control, as it allows consideration of the contribution of individual structures, and their spatial distribution, to fuel structure and fire hazard.

Advantages

- Extremely flexible.
- Consistent with the heterogeneous spatial pattern of pre-settlement ponderosa pine forests.
- Readily accommodates non-tree vegetation and dead wood.
- Well-suited to disturbance hazard reduction and structural restoration.

Disadvantages

- The flexibility and subjectivity of this approach will not suit all preferences.
- Marking is relatively complex and requires a knowledge of ultimate treatment objectives and the ecological rationale behind retention and harvest decisions.
- Ensuring continuity of direction through time requires clear documentation of treatment intent and application.

Area Control

What Is It?

Area control methods regulate stocking by allocating proportions of the stand to different age classes or structural conditions. The Unit Area Control method (Hallin 1959) and similar approaches (e.g., Youtz et al. 2008) subdivide the stand into areas of different existing or desired conditions, each of which is assigned a parallel but distinct treatment schedule. Target proportions for the total stand area occupied by each structural condition may be specified. A similar approach would be to assign target proportions of the stand to vegetation occupying different canopy layers (or heights, growth habits, etc.). The task of management is then to maintain these target proportions across cutting cycles.

An alternative approach is to specify a proportion of the total stand area to be harvested in each harvest entry (e.g., 20%) and then distribute this area across the stand in one or more groups. Assuming successful regeneration in the harvest openings, the number of cohorts in the multi-aged stand can be obtained by dividing 100 by the proportional area harvested in each cutting. Again, assuming successful regeneration and equal proportions of the stand harvested at each entry, the resulting stand would be balanced. Varying the proportion of the stand harvested from one entry to the next—mirroring natural disturbance regimes—will produce an unbalanced stand.

Area control, therefore, manages the stand as a series of small (sometimes very small) even-aged units. Because this approach is area-based, it is most suited to group selection and variable density thinning. It could also be applied in aggregated variable retention and irregular shelterwood systems. In all cases, retention of live trees, snags, and down wood within gaps is possible and may be desirable for many reasons (e.g., seed source, functional continuity, aesthetic value). Additionally, managing stands using area control does not preclude thinning and other intermediate treatments.

Application in Ponderosa Pine Stands

A common tendency when implementing area control is to allocate the structural conditions, canopy layers, or proportional area harvested into identically-sized, geometrically-shaped areas. These shapes are not consistent with the natural model of forest development and disturbance processes (in any forest type, and especially ponderosa pine). Application of area control therefore benefits from the intentional creation of irregularly-shaped and sized harvest areas. This may reduce operational efficiency but has other benefits, such as reducing the risk of wind damage. Area control is not immediately compatible with the ICO approach (which focuses on numbers of trees, not area, box 5). However, spatial heterogeneity could be incorporated into area control by varying the harvest gap shapes and sizes across the stand and between entries.

Advantages

- Conceptually simple, but with opportunities to scale for more complexity.
- Greatly simplifies marking and periodic stand examination requirements compared to many multi-aged stocking control and harvesting approaches.
- Approaches that designate structural conditions can be intuitively linked to management objectives, as can harvest shapes and sizes.

Disadvantages

- Documenting and tracking the location of areas treated at each cutting can become administratively complex over time.
- Without intentionally building heterogeneity into treatment design, area control can produce relatively simple stand structures without a direct natural analog and with limited aesthetic appeal.
- Large even-aged patches created by large group openings have some of the disadvantages of even-aged plantations.

Volume Control

What Is It?

Volume control methods emphasize balancing harvest removals and volume increment over the cutting cycle to ensure the sustainability of stand structure. Two volume control-based methods have been formally described. Informal or undocumented approaches almost certainly exist. In each of the documented volume control-based approaches—the plenter system (e.g., Schütz 1994) of central Europe and the volume control-guiding diameter limit (volume-GDL) method (Guldin and Baker 1998) of the southeastern U.S.—the balance between volume increment and harvest removals dictates the allowable cut at each harvest entry, but this guiding principle is supported by other structural rules.

- The plenter system is the oldest documented system for managing uneven-aged stands and is a management framework and philosophy as well as an approach for stocking control. The plenter system uses single-tree selection harvests with a short cutting cycle that produces stands containing trees of all size classes arranged in an intimate spatial mixture. The focus of plenter stocking control is maintaining a target “steady-state” (equilibrium) diameter distribution in which volume increase from ingrowth and progression through size classes balances harvest removals and mortality (Schütz 2006). The idealized form of this equilibrium distribution is the reverse-J, but many local variants of the plenter use a rotated sigmoid. This practical application suggests that there is some flexibility around the target diameter distribution (O’Hara 2014). Harvesting comes from the upper end of the distribution according to a target size determined by management objectives, typically product-related.
- Volume-GDL is less restrictive than the plenter system because it does away with a target diameter distribution. Like the plenter, volume-GDL requires a stand inventory before each harvest entry to determine volume increment (the allowable cut) over the cutting cycle. The allowable cut is apportioned across the growing stock using a guiding diameter limit. This limit is the size class in which a cumulative tally of growing stock volume, beginning at the upper end of the size distribution, meets the allowable cut (Guldin and Baker 1998). Marking seeks to “cut the worst and leave the best”, regardless of the guiding diameter limit. When trees above the guiding diameter limit are retained, an equivalent volume must be removed from the classes below the limit.

Application in Ponderosa Pine Stands

The principle of limiting harvest to volume increment over the cutting cycle has obvious parallels to sustained yield forest management practiced at large spatial scales and has broad applicability within ponderosa pine forests. On its own, however, the principle provides little guidance on stocking control in multi-aged stands. Additional criteria are required to assign the allowable cut (volume increment over the cutting cycle) to size or age classes and ensure regeneration of new cohorts, hence the diameter distribution and cutting rules that are applied concurrently in the plenter and volume-GDL methods. Of the two methods, volume-GDL is the more flexible and the most suited to ponderosa pine forests. Plenter stocking control has never been effectively demonstrated in a species as shade intolerant as ponderosa pine and is most suited to an intensive management style that is unlikely to be widely applicable.

Advantages

- The core guiding principle of volume control is simple and extremely flexible.
- Conceptual simplicity provides freedom to design supporting structural rules to suit stand and site characteristics and management objectives.

Disadvantages

- Provides no guidance for implementation or regenerating new cohorts.
- Requires a detailed inventory before each harvest to calculate the allowable cut.
- Marking can be challenging and benefits from the ability to visually estimate volume.

SDI Allocation

What Is It?

Under SDI (Stand Density Index; Reineke 1933) allocation, the practitioner specifies a target SDI for the stand and allocates this SDI between different diameter classes (or other structural categorizations, such as height, species, canopy layers) to achieve the desired stand structure. After this allocation, the target number of trees in each diameter class is computed (Long 1996; Long and Daniel 1990). When SDI is allocated across diameter classes, a diameter distribution is used to identify the number of trees for each diameter class. The diameter classes may be as narrow or wide as desired (e.g., diameter classes equivalent to understory, midstory, and overstory trees). Compared to the BDq approach, which also uses a diameter distribution, SDI allocation has more direct linkages with growing space occupancy because it couples tree density and size. SDI allocation is implemented using the summation-based approach to calculating SDI. In this approach, SDI is calculated for each inventoried tree, or for groups of trees with identical diameter, and then summed across trees (Long and Daniel 1990). This form of SDI calculation is suitable for multi-aged stands.

SDI allocation is compatible with any multi-aged regeneration harvest method.

Application in Ponderosa Pine Stands

SDI allocation is conceptually suited to ponderosa pine forests because it is based on a measure of growing space occupancy—SDI—that accounts for tree size; large trees in uneven-aged ponderosa pine stands typically account for a high proportion of total basal area, but have lower site resource use, per unit basal areas, than small trees (Fiedler and Cully 1995).

To our knowledge, SDI allocation has not been widely used in operational settings in ponderosa pine forests, but several research articles provide working examples of this method in research settings from across ponderosa pine's range (e.g., Cochran 1992; Fiedler and Cully 1995; Long 1996, 1998). For most resource management objectives on public land in the northern Rocky Mountains, implementing a relatively streamlined version of SDI allocation, in which each cohort is assigned a diameter class and allocated SDI, should be sufficient.

Advantages

- SDI is a widely-used measure of relative density that is likely to be familiar to most silviculturists and is linked to growing space occupancy.
- Provides quantitative density targets to aid harvest planning and growth projections.
- Flexibility over the number of diameter classes to include allows the user to alter the level of complexity involved.
- A wide range of structural metrics—e.g., canopy layers—can be used to develop diameter classes, which may be helpful in visualizing possible stand structures.

Disadvantages

- Application requires monitoring the number of stems in each diameter class during marking, which may become complex when larger numbers of diameter classes are used.
- Focuses on live trees without consideration of other structural elements or their spatial distribution.
- Published SDI maxima by forest type, used as a reference point for allocating SDI, may underestimate stand densities found at small spatial-scales, such as small stands or large patches within stands.

BDq

What Is It?

The BDq, or q-factor, approach is implemented by regulating the diameter distribution of the stand—with diameters used as a proxy for age. Users specify three parameters of this distribution in order to produce different structural outcomes: (1) desired residual (post-harvest) basal area (the “B”); (2) the diameter of the largest regulated trees in the stand (the “D”), and (3) the ratio of the number of trees per acre in successive diameter classes (the “q” factor). The target diameter distribution described by the q factor is a perfect negative exponential—the reverse-J. A stand that conforms to this distribution is said to be balanced i.e., it assigns an equal area (or amount of growing space) of the stand to each diameter class. Reducing the size of the q factor shifts the allocation of growing space toward larger trees, while increasing the q factor does the reverse (see box 4). At each harvest entry, the BDq method is implemented by harvesting trees from diameter classes with excess stems, relative to the target distribution, and avoiding harvesting in classes where deficits exist—these deficits can also be compensated by retaining additional trees in adjacent classes

A variety of modifications to the standard BDq system have been proposed in efforts to mitigate some of the shortcomings of this approach (Guldin and Baker 1998). The BDq approach is most-commonly associated with single-tree selection, but published examples of its use in group selection harvests also exist (Powell 2018).

Application in Ponderosa Pine Stands

Specifying a suitable level of residual basal area (“B”) is the most important of the three BDq parameters (Fiedler 1999; Guldin and Baker 1998). In ponderosa pine stands, a B of 50 to 80 ft² per acre is common. Maximum tree diameter (“D”) is the next parameter to determine and could be specified with ecological or economic rationale. Finally, in most circumstances, tailoring the BDq system to ponderosa pine forests will require a relatively low q-factor (1.1 to 1.5) (e.g., Alexander 1986; Fiedler and Cully 1995) to minimize dense, over-crowded understory conditions and increase basal area allocation to the larger trees.

A variety of modifications to the standard BDq system have been proposed in efforts to mitigate some of the shortcomings of this approach (Guldin and Baker 1998). One of these modifications that is relevant for management objectives requiring production and retention of large trees is to reserve a portion of the total basal area for trees exceeding the D parameter of the BDq (Fieldler and Cully 1995).

Advantages

- Provides detailed, quantitative marking targets, which some users will prefer.
- Conforming to the target distribution across equal length cutting cycles should produce even timber yields of predictable size classes through time.
- The BDq method is well documented, with many published examples.

Disadvantages

- Complexity in developing target stem densities for diameter classes.
- Requires a detailed inventory of stems by diameter class at each harvest entry.
- Complex, time-consuming marking.
- More rigid than most other stocking control methods. Adhering to the target distribution may be a constraint on management freedom.
- The reverse-J diameter distribution produces a relatively narrow range of potential stand structures that are less “messy” (heterogeneous) than commonly found in unmanaged uneven-aged stands. Additionally, many other sustainable distributions exist and could provide consistent timber yields.
- The reverse-J distribution allocates more growing space to small trees than will be necessary for most objectives.

Cutting Cycle

The *cutting cycle* refers to the time interval between harvests (O'Hara 2014) and is a fundamental property of a multi-aged system. A parallel can be drawn to rotation length in even-aged silvicultural systems, as both terms refer to the frequency of harvesting. However, rotation length in an even-aged stand is also equal to the maximum age that the oldest (and only) cohort will attain before harvest. This is not the case with the cutting cycle.

In common with rotation length, logistical and economic factors are often as much a consideration in selecting a cutting cycle as biological factors. The belief that multi-aged silviculture requires frequent and regular harvest entries (e.g., every 10th year) contributes to the common perception that multi-aged systems are complex and unwieldy. While it is certainly true that multi-aged systems may employ relatively short cutting cycles, which helps adhere to a target diameter distribution or stand structure, this is not necessary. In fact, considerable flexibility exists over both the average cutting cycle length and the variability of the cycle.

Factors influencing the cutting cycle can be understood by considering both cutting cycle length and variability. Considering these elements of the cutting cycle separately also illustrates the true flexibility to tailor the cutting cycle to stand management objectives and constraints in a multi-aged silvicultural system.

- **Cutting cycle length.** Cutting cycle length refers to the average time between consecutive harvests in a multi-aged stand. An important relationship exists between cutting cycle length, harvest removals, and subsequent growth. For a given site, longer intervals between harvest entries allows more time for biological processes (e.g., vegetation growth) to occur than shorter cutting cycles. If a stand is managed using residual stocking or diameter distribution targets, then longer cutting cycles result in more departure from this stocking/distribution target by the end of the cutting cycle. Consequently, a higher intensity harvest (i.e., more volume removed) is required to return the stand to the target structure (fig. 6.20). Because longer intervals between harvests provides more time for the stand to accrue volume, these intervals may be helpful in circumstances where economic recovery of harvest costs is relatively high. A corollary is that other things being equal, more productive sites allow for shorter cutting cycles for a given economic viability threshold than less productive sites. Similarly, where management objectives require the maintenance of

a specific, narrow range of stand structure, shorter cutting cycles will be more suitable, for a given site quality.

In practice, a range of other practical considerations are also likely to influence the choice of cutting cycle length. Factors that may affect the cutting cycle length include (1) the sensitivity of soils, vegetation, and wildlife to harvesting operations and equipment, (2) accessibility and availability of marking and harvesting personnel, (3) recreational use, and visibility of the site to rural or urban populations.

In multi-aged systems, harvests typically serve both regeneration and stocking control functions. Hence, the desired number of cohorts in the stand (relative to ecological or product-based maximum tree age) may also influence the choice of cutting cycle. However, there may be cases where intermediate treatments are necessary between standard cutting cycles. For instance, a cutting cycle of 30 years might benefit from prescribed burning every 15 years to maintain low fire hazard. Given this long list of factors influencing cutting cycle length, choosing a cutting cycle length is likely to be a compromise between many potentially competing biological, economic, logistical, and functional drivers.

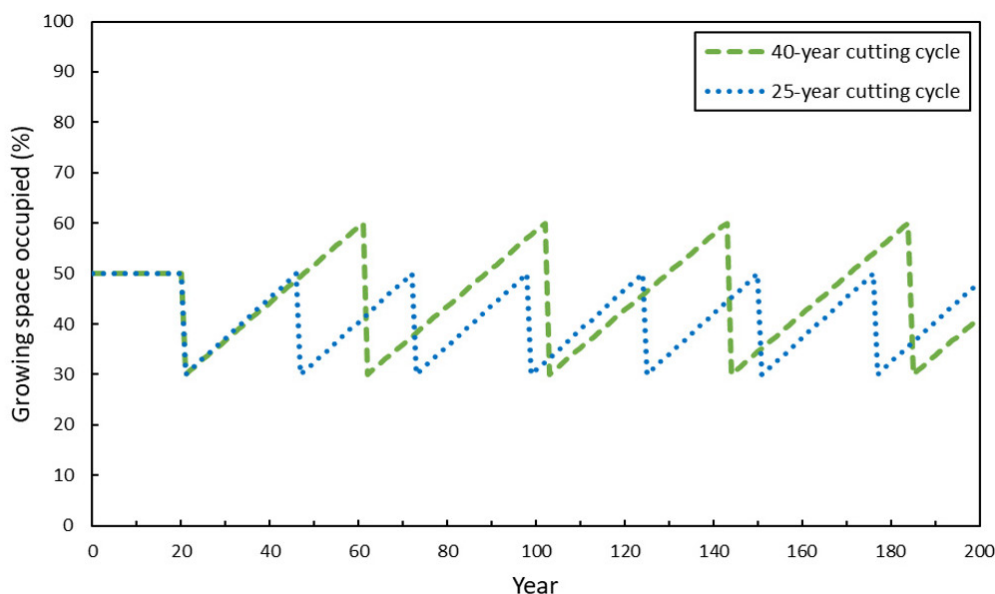


Figure 6.20—A conceptual depiction of changes in growing space occupancy in two stands over a 200-year period, through multiple cutting cycles. One stand has a 40-year cutting cycle, which includes four regeneration harvests and the other stand has a 25-year cutting cycle, which results in six harvests over the same period of time. The stand with the longer cutting cycle exhibits much greater variability in growing space occupancy than the stand with a 25-year cutting cycle.

- **Cutting cycle variability.** Cutting cycle variability refers to the amount of variation in the time between consecutive harvests in a multi-aged stand. An average cutting cycle length of 40 years could be produced by (1) regular harvests every 40 years (no variability), by (2) harvest intervals that vary between 20 and 60 years (high variability), or (3) by any other combination.

The degree of variability in the cutting cycle has consequences for the desired range of future conditions in the multi-aged stand and for stand management objectives. A high degree of variability through time in the cutting cycle results in a wider range of stand conditions than an identical, average cutting cycle that has low variability. This may have undesirable consequences depending on stand and site conditions. Management objectives that require stand structures to be maintained in a relatively narrow range will also be less attainable in a regime that allows high variability in cutting cycle length. Similarly, stocking control methods, such as the BDq and the plenter system, are not effective when the cutting cycle is highly variable through time. However, high cutting cycle variability does have some advantages.

As noted elsewhere, multi-aged management does not need to be rigid or resource intensive. One way to increase flexibility and reduce management burden is to accept variability in the cutting cycle. Accepting variability in the cutting cycle does not prevent the specification of a target cutting cycle length. It does, however, permit resource limitations—human resources, physical and financial resources, time—to influence the timing of re-entry. Accepting variability in the cutting cycle allows for opportunistic management interventions, for example, (1) to coincide with availability of marking personnel or harvesting contractors, (2) to capitalize on pulses of funding, or (3) to schedule treatment of the target stand at a time that allows merchantable timber to be combined with other local timber sale contracts to increase financial viability. This flexibility is particularly valuable for relatively inaccessible stands that are further from district offices and/or processing facilities.

Relatively high cutting-cycle variability is also consistent with many natural disturbance processes and the resultant

Multi-aged management does not need to be rigid or resource intensive, and one way to increase flexibility and reduce management burden is to accept a degree of variability in the cutting cycle.

natural model of forest development. In unmanaged stands, irregular timing of natural disturbance events contributes to within-stand heterogeneity of structure. The absence of a regular interval between disturbance events also produces a wide array of possible stand structures and structural development pathways. This contributes to forest heterogeneity at meso- and landscape scales. Introducing variability in the cutting cycle helps emulate this natural model of forest development as part of a management strategy based around the principles of ecological silviculture.

In practical terms, a flexible approach to managing the cutting cycle using the principles of ecological silviculture might initially specify a target long-term average cutting cycle based on the assumed mean natural disturbance frequency for the target site. The actual time between harvest entries would then be allowed to vary around the mean from one harvest entry to the next, and from one stand to the next (if multiple stands are being managed using this approach). An important element of this ecologically-based approach is that, over the long term, some structural elements (e.g., a percentage of the live overstory) would be retained until these structures develop the characteristics of a mature or old forest. This length of time is termed the *recovery period* and is a key principle of ecological silviculture: *timing* (Palik et al. 2020).

In summary, the cutting cycle is an important attribute of a multi-aged management regime and incorporates both the long-term average length of time between harvests and variability in this interval. Adjusting cutting cycle length and regularity provides considerable scope to tailor the silvicultural system to site conditions, stand management objectives, desired range of variability in stand structure, and resource availability.

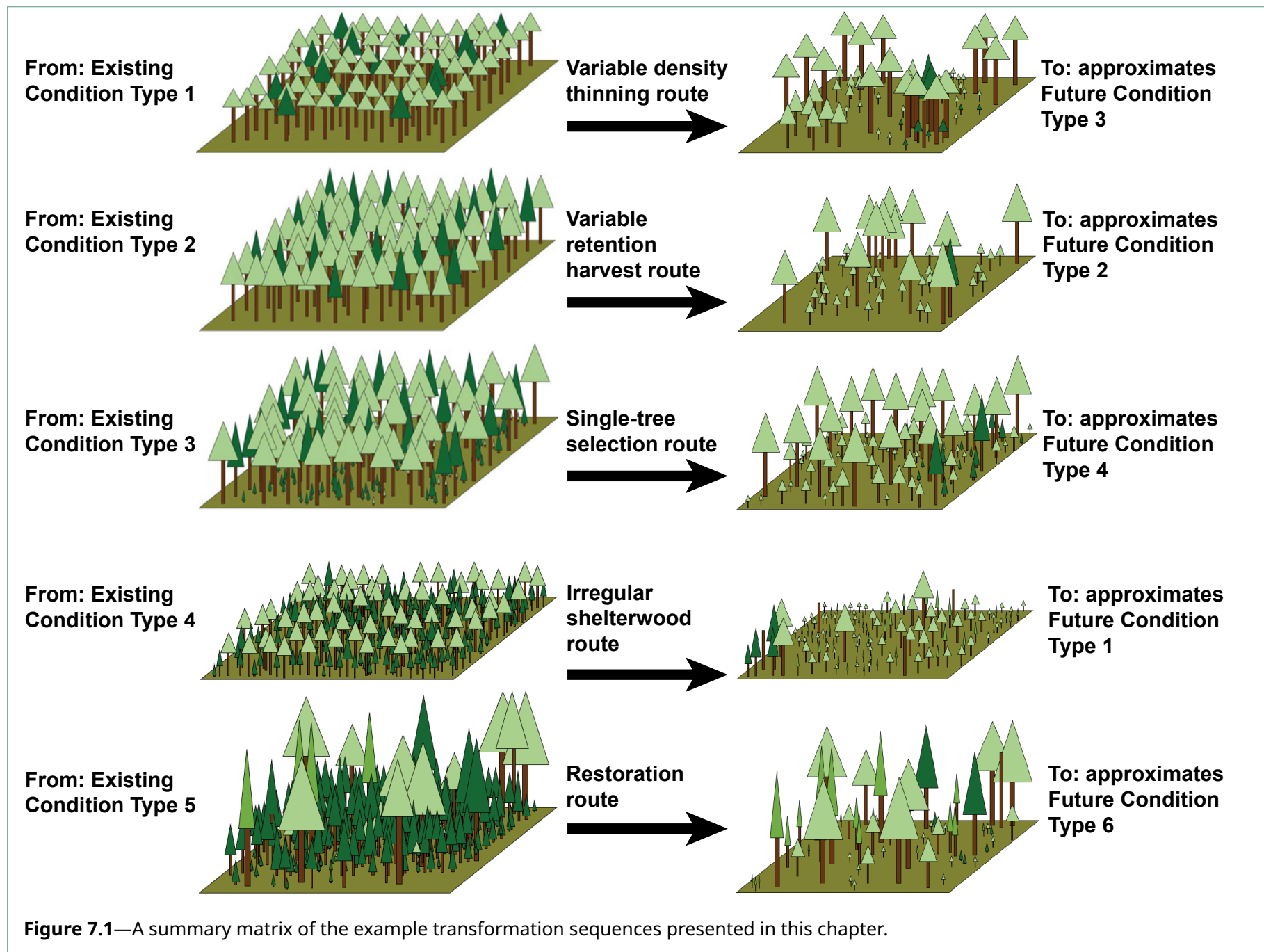
A range of cutting cycles is described in the literature for ponderosa pine forests. Earlier examples of multi-aged management in the inland northwest used heavier harvests and longer cutting cycles (40–75 years, Meyer 1934, in O'Hara 2002). More recent studies in ponderosa pine typically describe shorter cutting cycles of 10–30 years (Alexander 1986), 20–30 years (Fajardo et al. 2006; Fiedler 1999; Fiedler and Cully 1995; Schubert 1974) and 25–50 years (O'Hara et al. 2003). Each of these recent examples falls within the historical fire-return intervals for ponderosa pine forests in the northern Rocky Mountains and indicates the

consistency of feasible cutting cycles with natural disturbance regimes in this region (e.g., Arno et al. 1995, 1997; Hood et al. 2021).

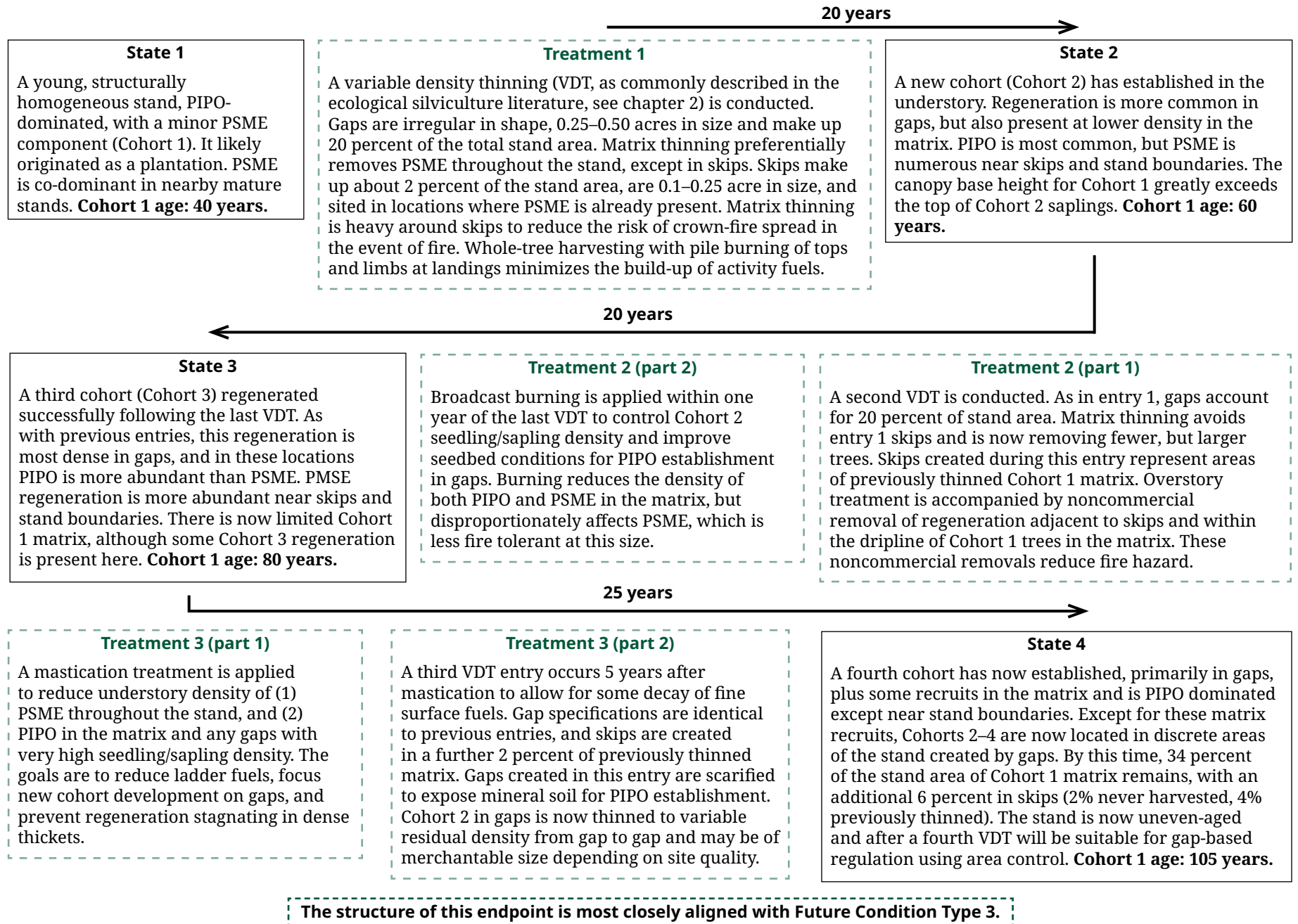
Chapter 7: A Matrix of Transformation Sequences

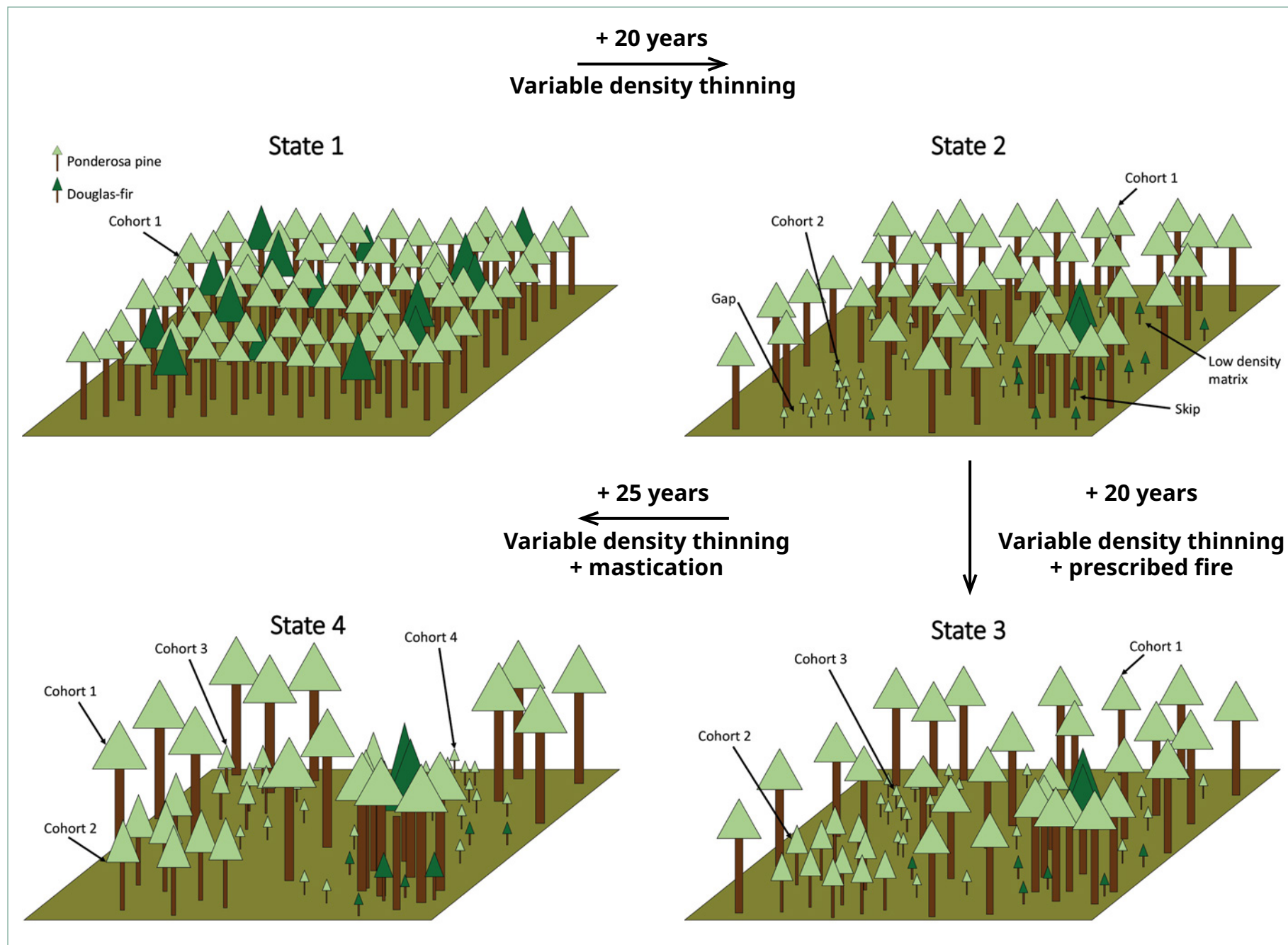
Throughout this guide, an emphasis has been placed on describing the unique set of conditions, objectives, and constraints that exist for each stand undergoing transformation, and then crafting a tailored transformation sequence. Because of the individual nature of each transformation, it would be counterproductive to include a set of predefined transformation sequences. Instead, this chapter presents several hypothetical examples of transformation sequences, each of which outlines a plausible set of treatments beginning from one of the existing condition types in chapter 4. These examples cover only a small number of the management options that exist (see chapter 6) and the ways these management treatments can be chained together in a transformation sequence. These examples cannot replicate the messy ecological reality. They do, however, illustrate how a transformation might unfold in ponderosa pine stands that exhibit structures now common in northern Rocky Mountain landscapes. Together with the case studies in chapter 8 of this guide, these examples add color to the inevitably simplistic conceptual presentation of the transformation process in previous sections of this guide.

Each of the example transformation sequences is described using a matrix of *states*—the condition of the stand at a particular point in time—and treatment paths. Tree names are abbreviated to standardized four-digit codes: ABGR – grand fir, LAOC – western larch, PIPO – ponderosa pine, and PSME – Douglas-fir. Descriptions of stand conditions and treatments are necessarily brief and tracking the number of cohorts present at any given time may not always be easy. For this reason, each transformation sequence is accompanied by a visual representation of the process using the simple “stick and triangle” cartoons used elsewhere in this guide. Figure 7.1 below provides an overview of the example transformation sequences that are presented in this chapter.

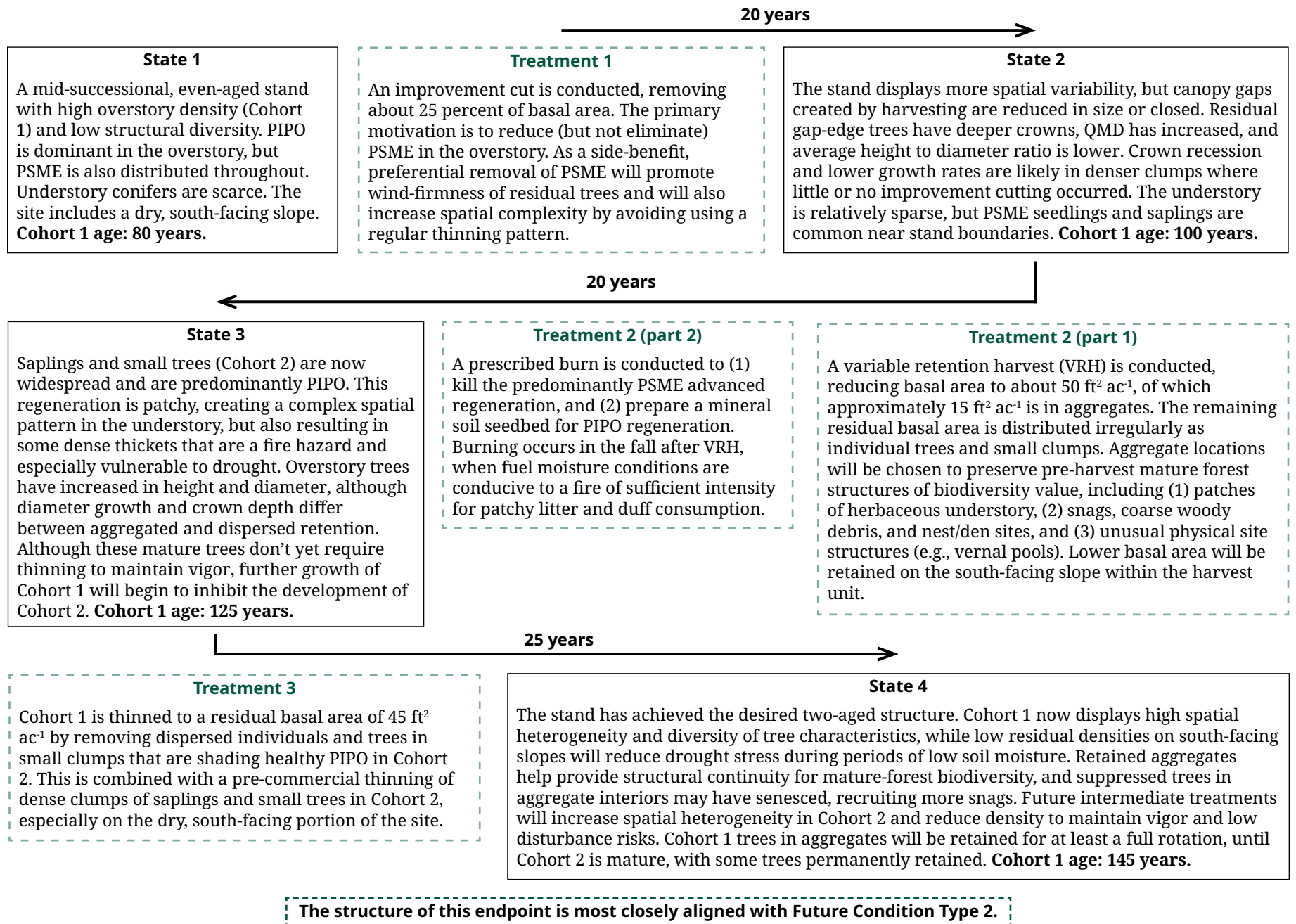


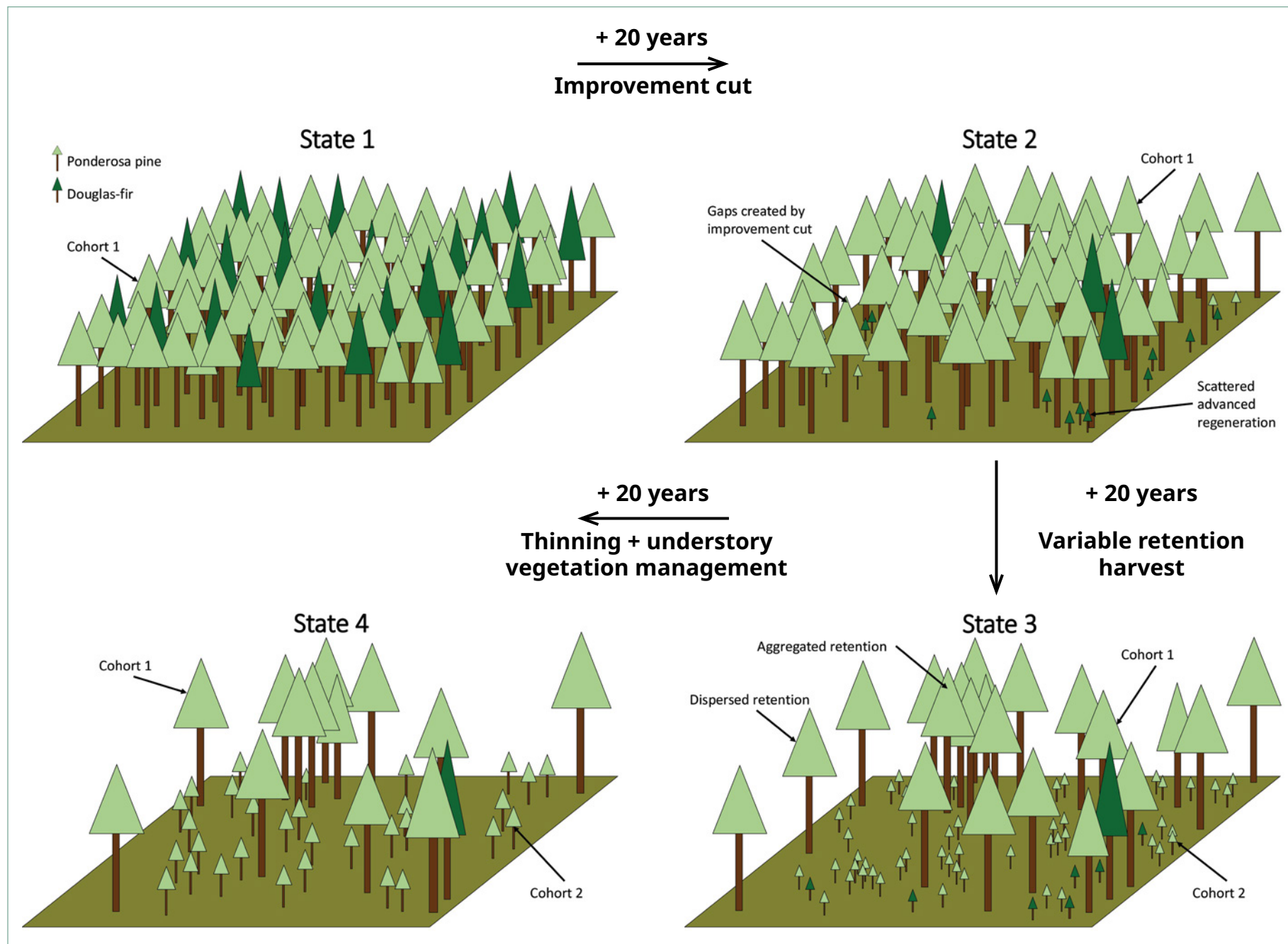
1. From Existing Condition Type 1 to uneven-aged structure with 4 or more cohorts regulated using area control—variable density thinning route



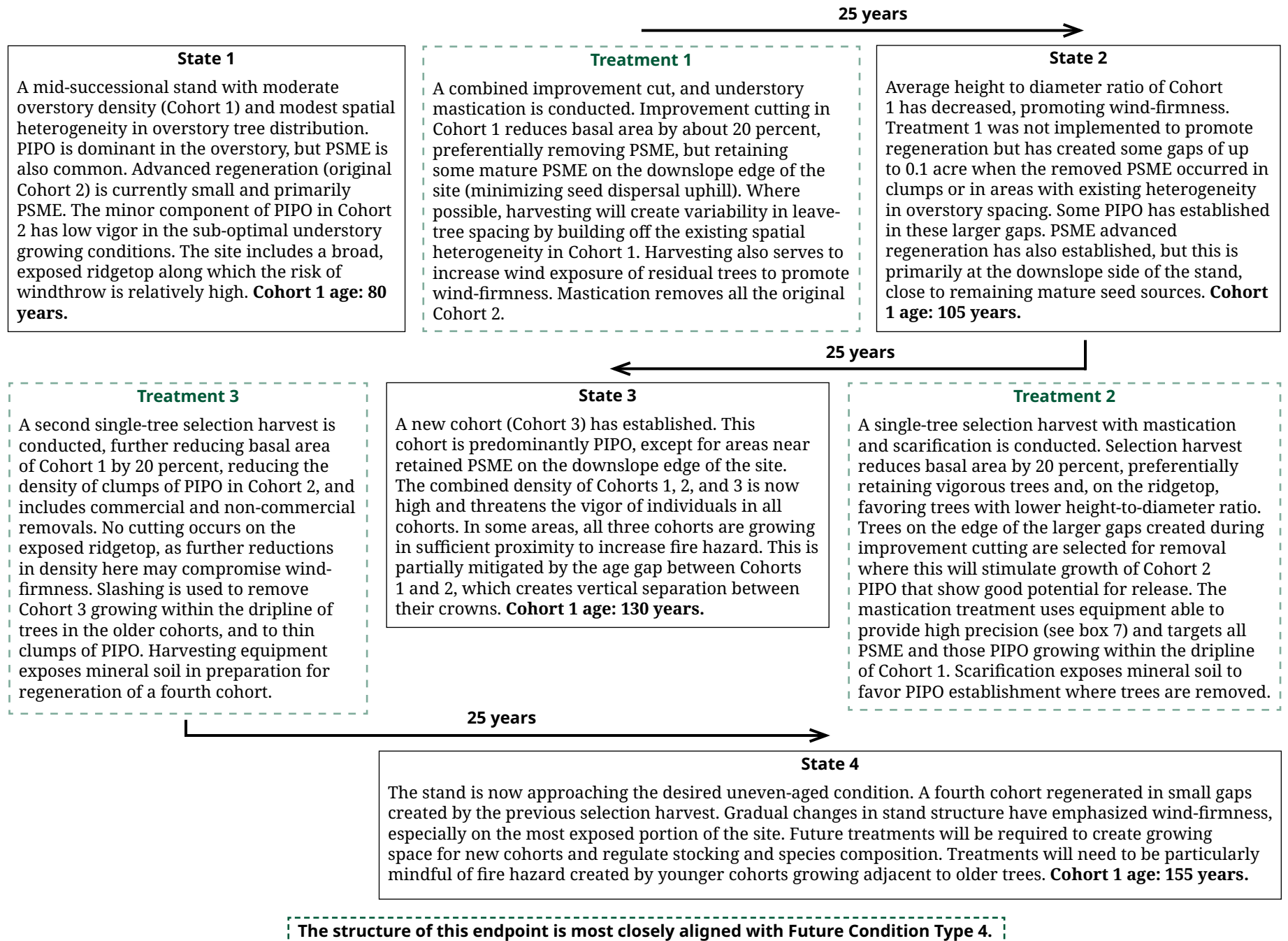


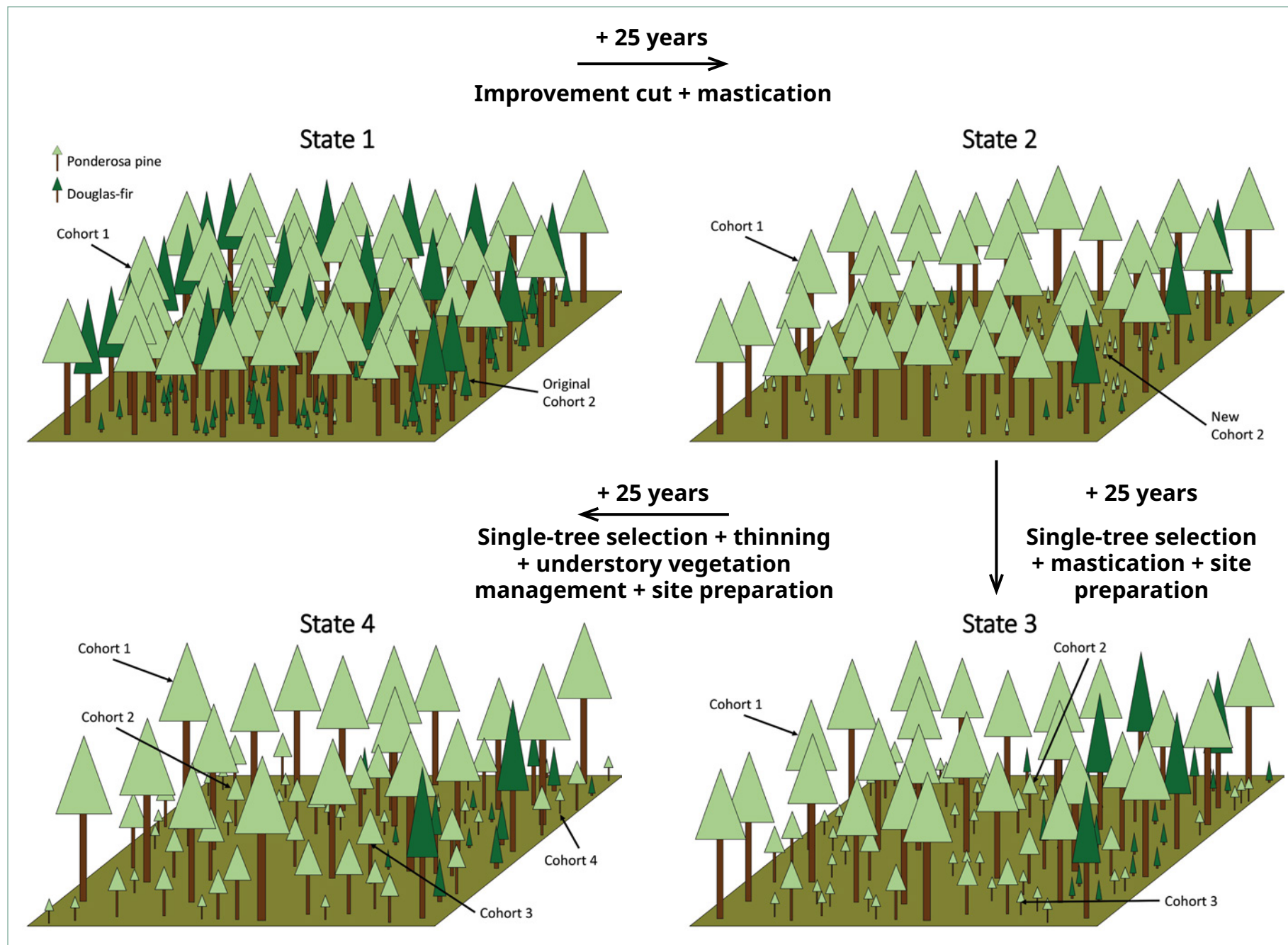
2. From Existing Condition Type 2 to an ecologically complex two-aged structure with low disturbance and climate risks—variable retention harvest route



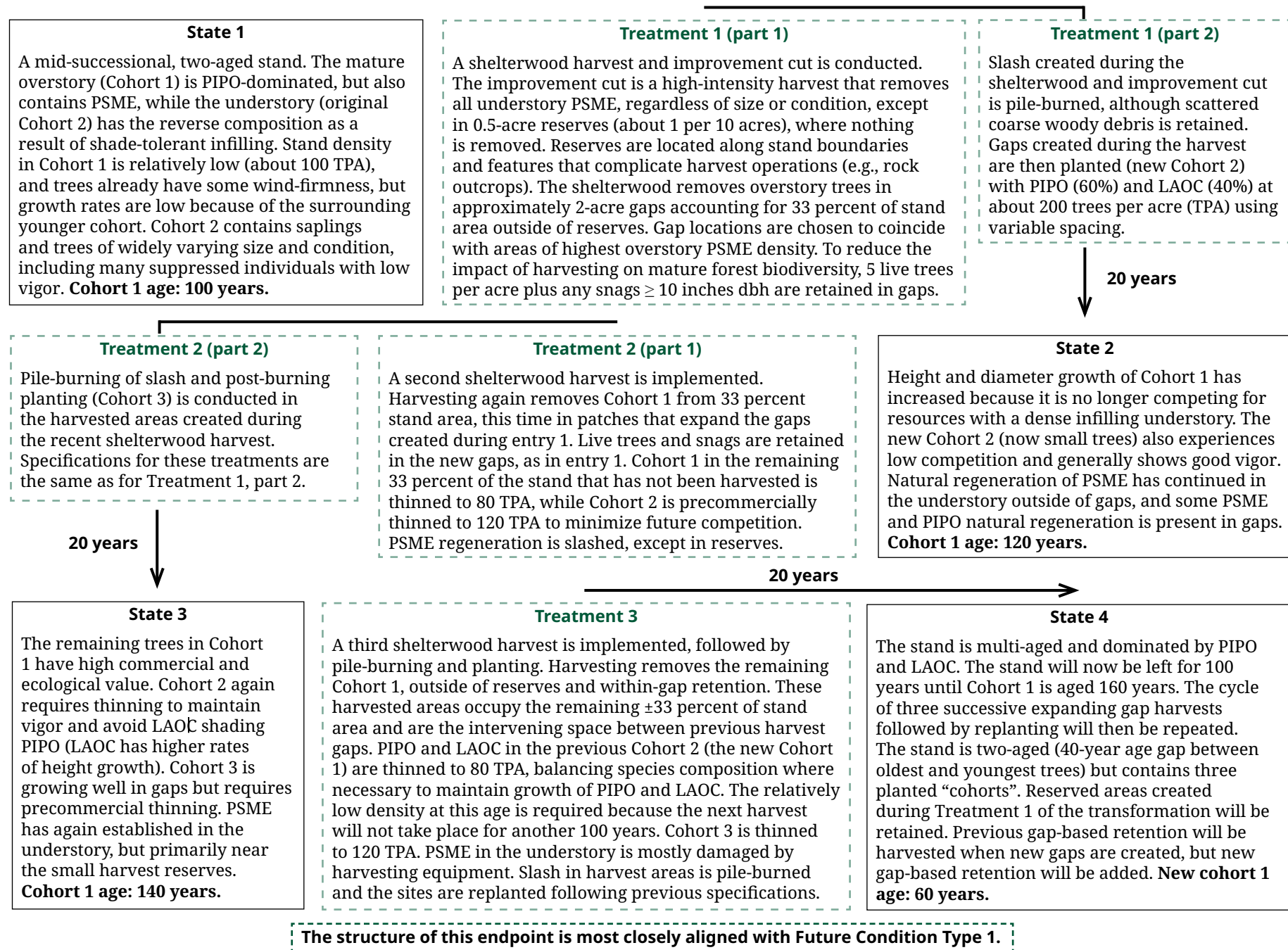


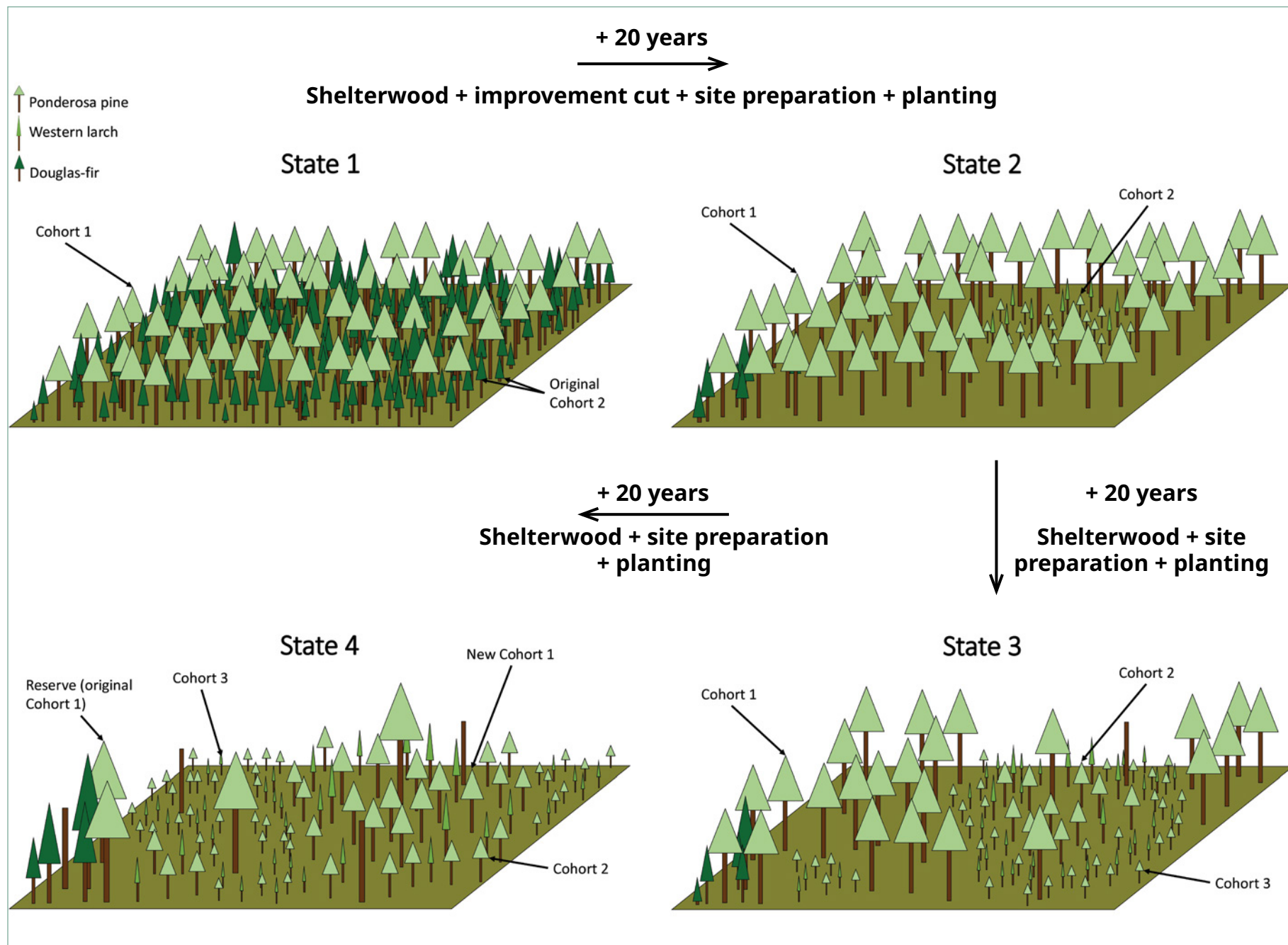
3. From Existing Condition Type 3 to a windfirm, pine-dominated stand with four cohorts on an exposed site—single-tree selection route



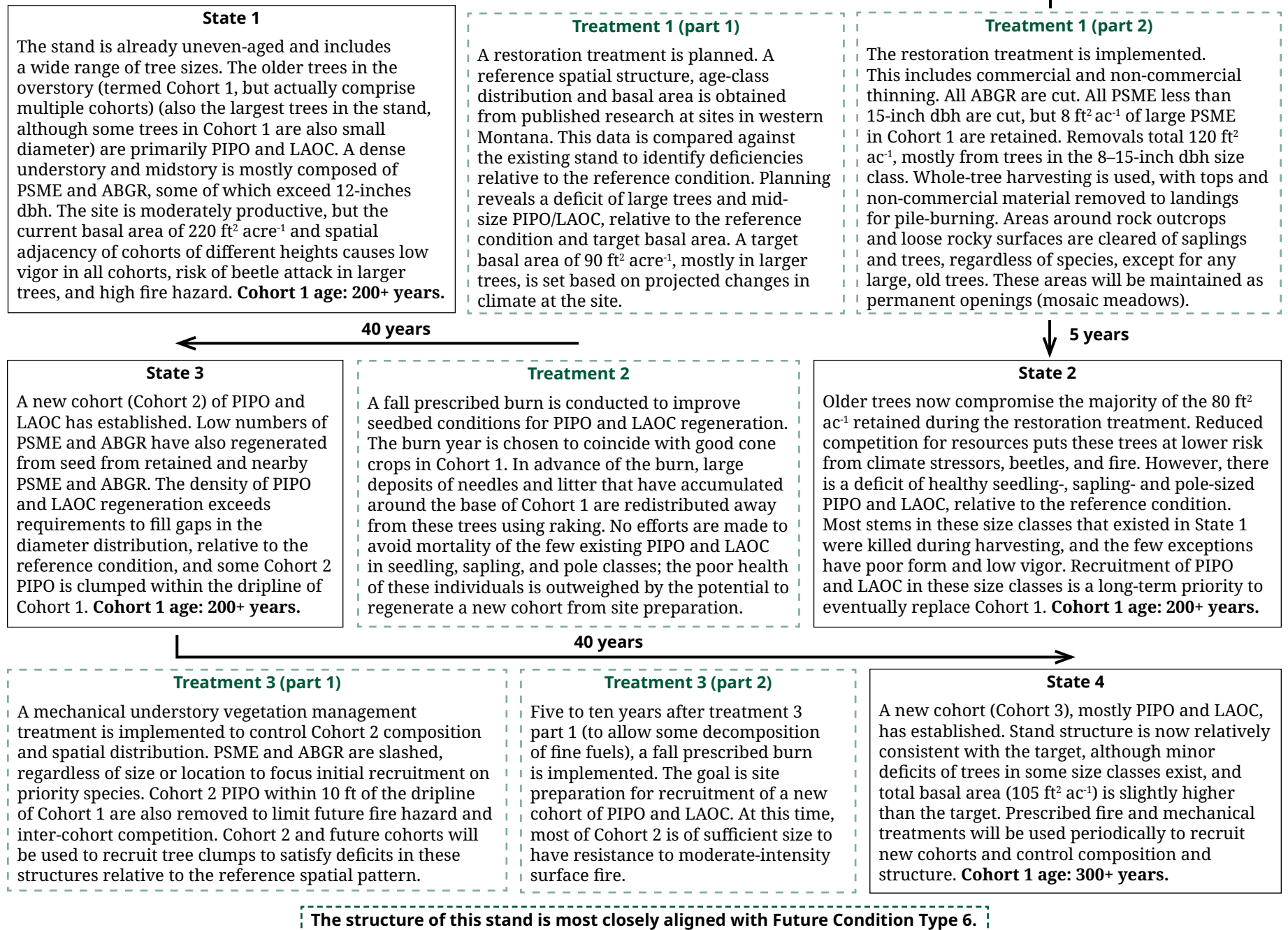


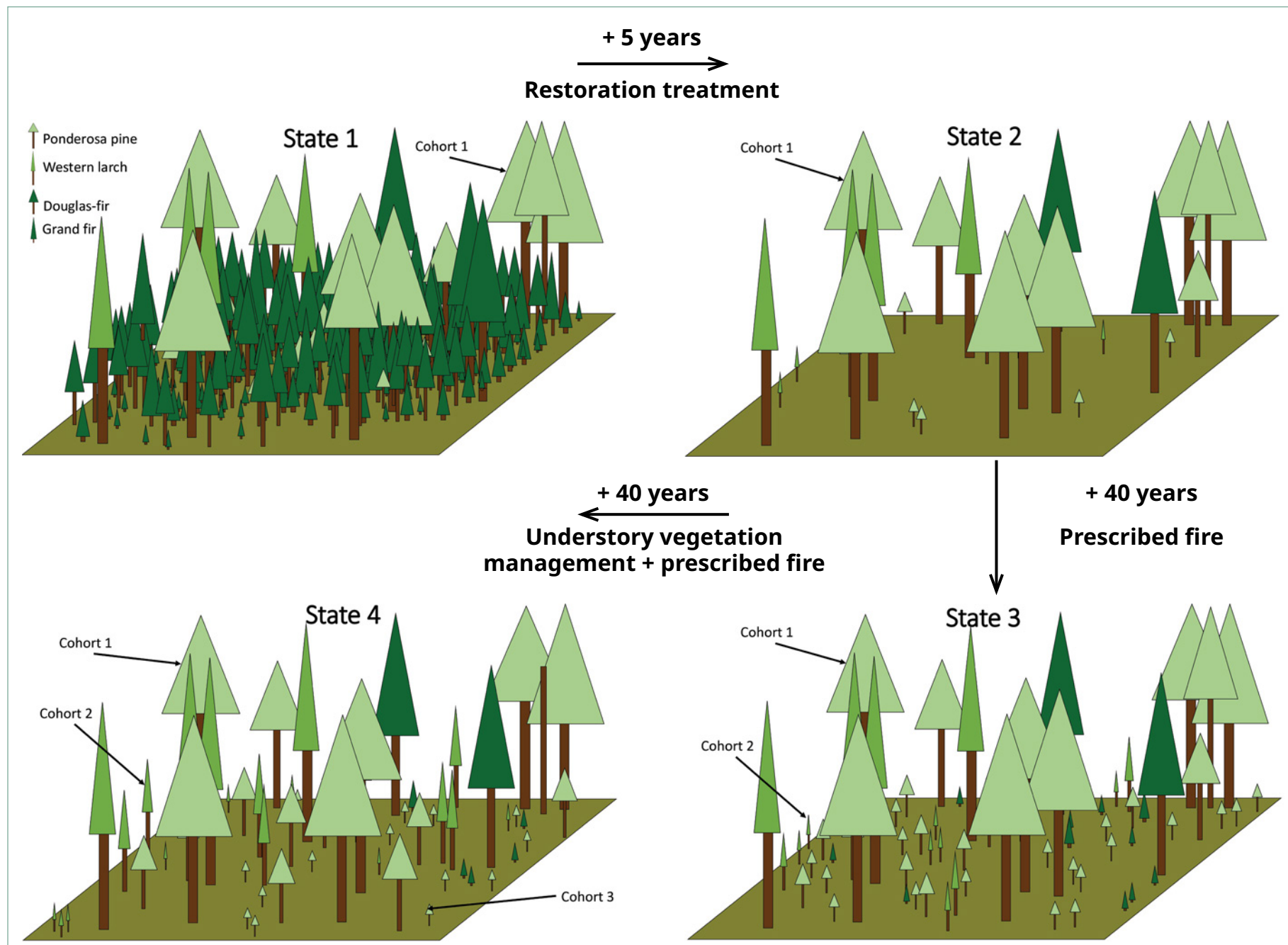
4. From **Existing Condition Type 4** to a two-aged ponderosa pine and western larch stand – expanding gap irregular shelterwood route





5. From **Existing condition Type 5** to a structure that approximates a presettlement, old-growth pine-dominated stand – restoration route





Chapter 8: Case Studies

In this section of the guidebook, we provide several case studies (fig. 8.1) of silvicultural transformation in ponderosa pine stands in the northern Rockies. Case studies can help translate conceptual ideas and hypothetical examples, such as those previously described in this guidebook, into the more complex reality. The examples that we present below are from stands in the first one to three decades of the transformation process. They exhibit varying transformation sequences and varying degrees of premeditation in transformation planning. Although some case studies include data on initial and/or existing stand conditions, where such data is available, we focus on a narrative description of stands, management objectives, and transformation approaches.

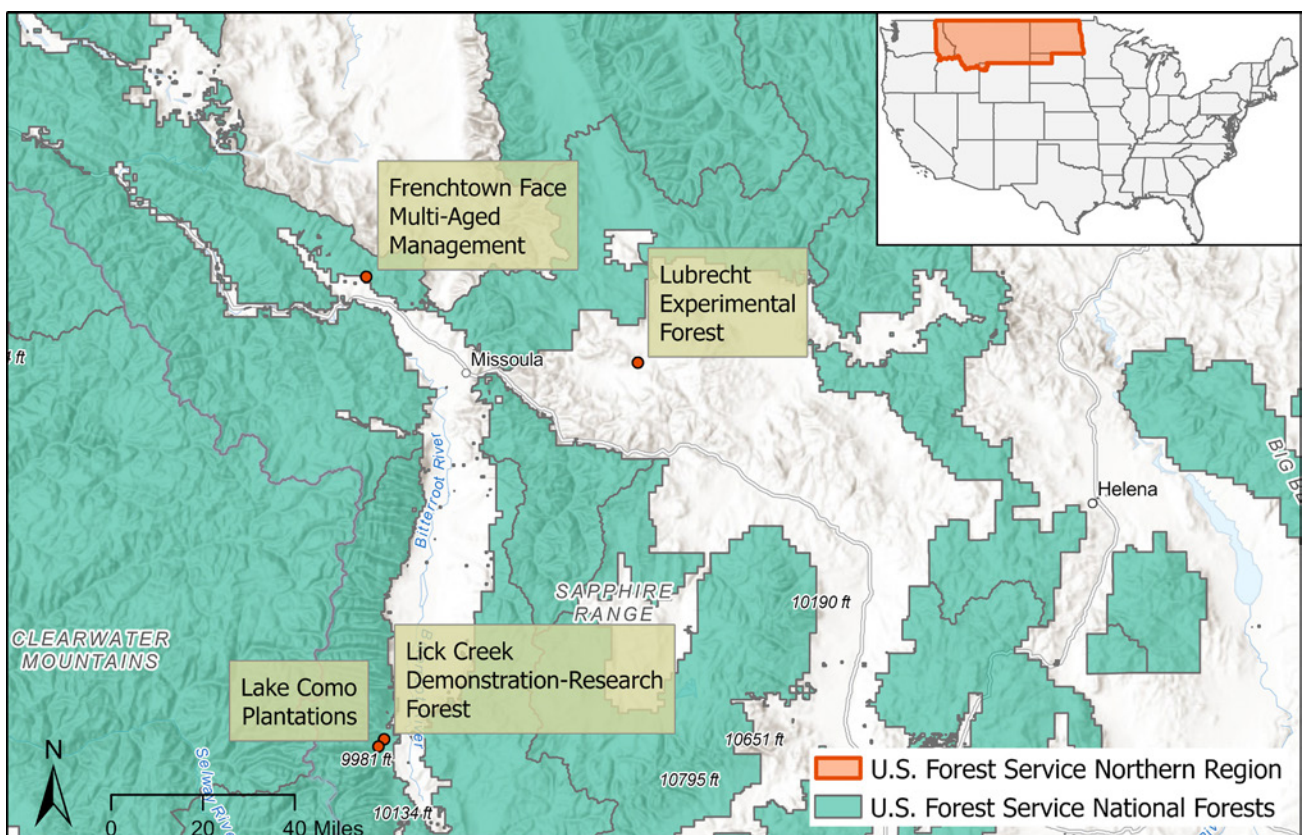


Figure 8.1—The location of case studies of silvicultural transformation to multi-aged structures presented in this section of the guidebook.

Two of the case study sites featured in this chapter are research forests, but all four sites are managed for objectives typical of public lands in the northern Rocky Mountain region, and all sites are subject to the types of operational constraints that are common in working forests. Although all four case study locations have good accessibility, the advantages that this brings are accompanied by

important management challenges, notably around recreation, aesthetics, and fire management in the WUI.

Lick Creek Demonstration-Research Forest: Irregular Shelterwood Pathway

The irregular shelterwood transformation pathway (“Lick Creek Irregular Shelterwood”) at Lick Creek Demonstration-Research Forest (“Lick Creek”) on the Bitterroot National Forest is one of three experimental treatment pathways implemented at this site in the early 1990s with the broad aim of ecosystem restoration.

Site history and pre-treatment stand conditions—

The Lick Creek Irregular Shelterwood unit was a second-growth stand that likely originated from natural regeneration following clearcut logging in 1906, prior to federal ownership. By 1991, the stand was beginning to transition to a two-aged structure as advanced regeneration—dominantly Douglas-fir—established a second cohort underneath the ponderosa pine-dominated overstory (fig. 8.2 inset). Therefore, the unit most closely resembled existing condition Type 3 (chapter 4). Pre-treatment stand structure is detailed in table 8.1. Before treatment, high stand density in the overstory caused reductions in vigor, thereby increasing susceptibility to bark beetles, while ladder fuel development in the understory had increased fire hazard.



Figure 8.2—Overstory and understory cohorts are visible in this photograph (main) from the “wet burn” area of the Lick Creek Irregular Shelterwood, now 30 years after the first shelterwood harvest in the transformation sequence. The inset image shows the denser overstory and multi-layered canopy of an untreated area.

Table 8.1—Summary data for the Lick Creek Irregular Shelterwood site and unit at the time of treatment (1991). Trees per acre, basal area and QMD apply to stems $\geq$ 1-inch dbh. Composition includes seedlings.

Site and pre-treatment stand summary (1991)	
Elevation (ft)	4,500
Habitat type	<i>Pseudotsuga menziesii/Vaccinium globulare</i>
Age (years)	80 - 85
Trees per acre	176
Basal area (ft ² ac ⁻¹)	117
QMD (inch)	11
Composition	Overstory: ponderosa pine (86%), Douglas-fir (13%) Understory: Douglas-fir (67%), ponderosa pine (33%)

Management objectives and desired future condition—

Within the broad goal of ecosystem restoration, management aimed to increase resilience to fire, insects, and disease, to improve wildlife habitat, aesthetic values, and recreational opportunities, and to restore an active fire regime. The desired future condition to satisfy these objectives is (1) an uneven-aged stand with a significant component of large-diameter trees plus younger cohorts to supply future replacements, (2) composition dominantly of shade-intolerant pines, and (3) lower stand density than pre-treatment.

Transformation sequence—

The planned transformation sequence called for repeated irregular shelterwood harvests followed by prescribed burns, progressively reducing the density of the oldest cohort (the overstory) while regenerating new cohorts. Entries were proposed on a 20–30-year cutting cycle. A selection system was envisaged for the stand following transformation to the desired multi-aged structure.

Treatment began in 1992 with an irregular shelterwood harvest that retained, on average, 52 ft² per acre basal area (exceeding the target stocking of 40 ft² per acre). Whole-tree harvesting was used to minimize slash accumulation. Delimbing occurred at landings, and this material was pile-burned, but tops above 6-inch diameter were scattered in the stand to provide nutrient inputs. Harvesting was followed by a prescribed burn that was implemented in 1993–1994 as an experiment. The irregular shelterwood unit was divided into sub-units representing four alternative treatment pathways (with three replicates of each pathway): (1) control (no treatment), (2) harvesting but no burning (“harvest only”), (3) harvesting +

wet burn (50 percent duff moisture content) (“wet burn”), and (4) harvesting + dry burn (16 percent duff moisture content) (“dry burn”).

The initial irregular shelterwood harvest was successful in increasing vigor among residual overstory trees, which responded with increased growth rates after a brief post-burn recovery period. As a result, the stand has recovered much of the harvest-related reduction in basal area (table 8.2).

Table 8.2—Stand summary data for the Lick Creek Irregular Shelterwood as of 2023, approximately 30 years after cutting and burning, displayed by treatment. Trees per acre, basal area and QMD relate to stems greater than 6-inch diameter at breast height.

2023 summary	No treatment	Harvest only	Cut + wet burn	Cut + dry burn
Age (years)	105 - 110	105 - 110	105 - 110	105 - 110
Trees per acre	132	68	54	62
Basal area (ft ² ac ⁻¹)	149	112	80	85
QMD (inch)	15	17	17	17
Composition: overstory	PIPO: 75%	PIPO: 81%	PIPO: 96%	PIPO: 91%
	PSME: 25%	PSME: 19%	PSME: 4%	PSME: 9%
Composition: understory	PIPO: 18%	PIPO: 32%	PIPO: 50%	PIPO: 55%
	PSME: 78%	PSME: 68%	PSME: 28%	PSME: 42%

Regenerating a new cohort was partially successful (fig. 8.2 main). Although harvesting did produce a pulse of regeneration, understory composition across much of the unit includes more Douglas-fir than envisaged (fig. 8.3).

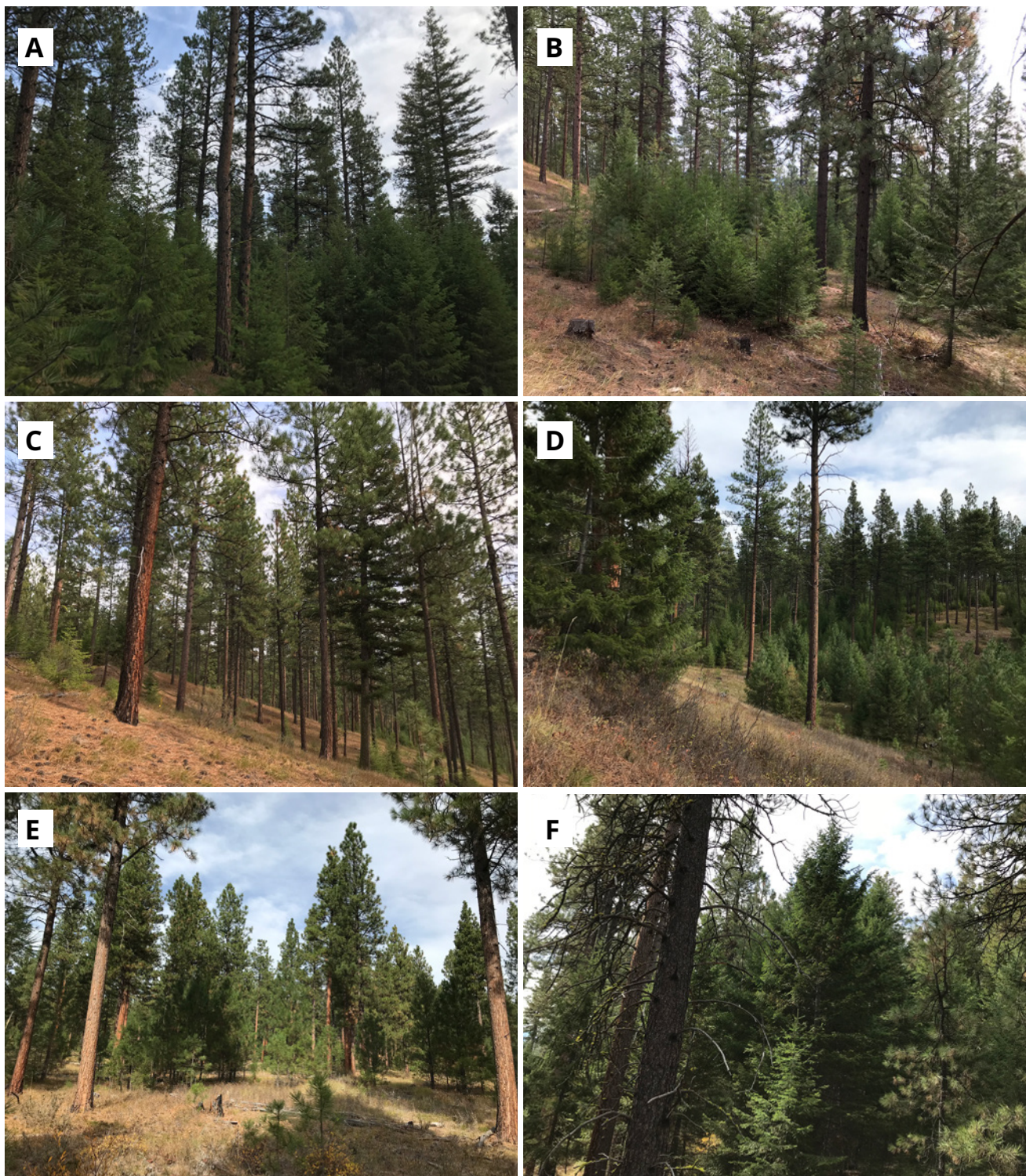


Figure 8.3—Understory seedlings, saplings and small trees are abundant and dominated by Douglas-fir in sections of the Lick Creek Shelterwood that received no prescribed burn (a and b). Understory Douglas-fir is also abundant in areas receiving a “wet burn”, although at a lower density than the “no burn” treatment. In the wet burn, regeneration tends to be distributed irregularly, scarce in some areas (c), but dense in other places (d). In areas receiving the “dry burn”, seedlings, saplings and understory trees are dominantly ponderosa pine (e), with Douglas-fir mostly found near retained overstory seed sources (f).

Possible causes of the continued dominance of Douglas-fir in the understory include retention of mature overstory Douglas-fir during harvesting and a lack of mechanical removal of larger advanced regeneration that had developed fire resistance at the time of the prescribed burn. Of the alternative treatment pathways, this problem is most acute in the “harvest only” and parts of the “wet burn” treatments. In these areas, large, contiguous patches of Douglas-fir, ranging in size from seedlings to midstory trees, are common. Understory density is lower in the “dry burn” treatment pathway, and more areas of this treatment have a ponderosa pine-dominated understory, but understory/midstory Douglas-fir remains common in the vicinity of residual overstory Douglas-fir. Therefore, it appears that the presence and location of retained overstory Douglas-fir is an important influence on understory composition.

Changes in fire hazard metrics—

As with any silvicultural treatments, changes in vegetation structure through time following harvesting and prescribed fire application at the Lick Creek Irregular Shelterwood unit have implications for subsequent fire hazard (see chapter 9 for a general discussion of multi-aged structures and fire hazard). Many metrics of fire hazard have been developed, including those related to understory, overstory, and their integrated structure (e.g., Agee and Skinner 2005). Figure 8.4 shows temporal changes in four such hazard metrics, calculated using FVS (Dixon 2002), from 1993 (one year after irregular shelterwood harvest) to 2005 (13 years post-treatment), and 2023 (30 years post-treatment) for each of the four treatment pathways.

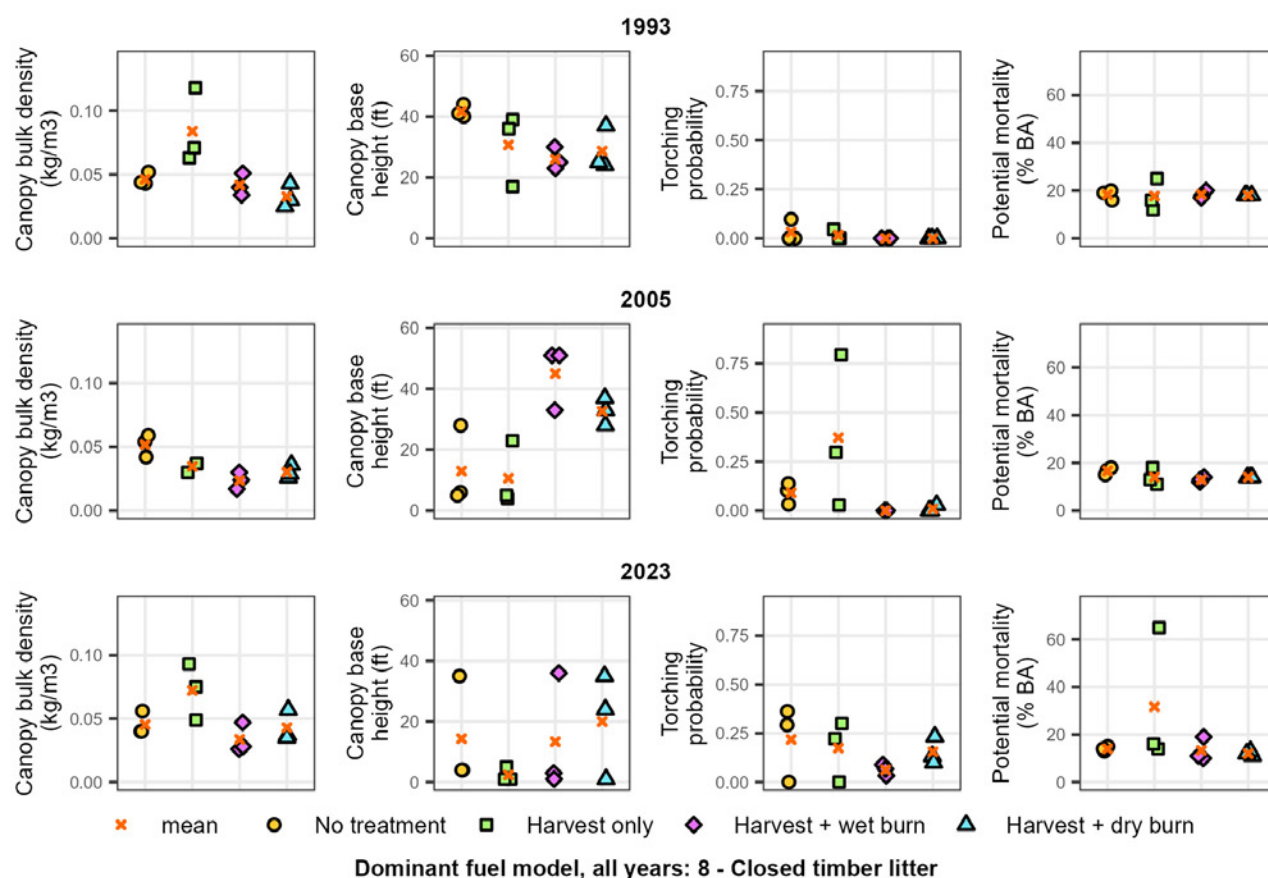


Figure 8.4—Temporal changes in canopy bulk density, canopy base height, potential mortality, and torching probability for forest in the Lick Creek Irregular Shelterwood study managed using four alternative treatment pathways. Hazard metrics were calculated using FVS. Note that FVS does not include trees shorter than 6 ft in height in its calculation of canopy base height, and the heights of many small diameter trees were not gathered during inventory. Potential mortality and torching probability for the fire hazard analyses presented in this chapter were modeled using severe, although not extreme, fire weather conditions (a simulated fall fire with wind speeds of 20 mph (9 m s⁻¹), temperatures of 80 °F (27 °C), and duff moisture content of 16 percent across the entire stand area).

The fire hazard metrics displayed in figure 8.4 suggest that the 1992 irregular shelterwood harvest and subsequent prescribed burning (where applicable) may have reduced fire hazard over relatively short post-treatment timeframes. The metrics also illustrate the complexity involved in comprehensive fire hazard management. The FVS simulations imply that, by 2005 (13 years post-harvest), (1) canopy base height was higher, and (2) canopy bulk density and potential mortality and torching probability during severe fire events were lower in the transformation sequences that involved harvesting followed by prescribed burning than in untreated units. By 2023 (30 years post-harvest), however, the difference in these hazard metrics between the harvest + burn pathways and untreated areas was much reduced. Canopy base height remained

higher in Harvest + dry burn treatment units than in untreated units, while canopy bulk density and torching probability were lower in harvest + wet burn units than in untreated units. In the harvest-only treatment pathway, canopy bulk density and predicted mortality were lower 13 years post-harvest than in untreated areas, but by 30 years post-harvest, the only metric in which the harvest only pathway outperformed the no-treatment control was torching probability (lower in the harvest only). In most other respects the harvest only pathway appeared to have little or negative effects on fire hazard, compared with the control. These negative effects were likely a result of dense post-harvest Douglas-fir regeneration.

Figure 8.4 presents only a small number of fire hazard metrics, and this analysis was far from exhaustive, but these estimates illustrate the complexity of balancing fire hazard reduction—and, in fact, balancing different components of fire hazard—with other treatment objectives while accomplishing transformation to multi-aged structure. This exercise also illustrates the important temporal dimension to changes in vegetation structure and fire hazard after treatment. Treatments implemented in the 1990s at Lick Creek were not designed to reduce fire hazard over a 30-year post-treatment period, which is beyond the typical longevity of fuel treatment effectiveness in the habitat types found at Lick Creek (Hood et al. 2020). However, the second phase of treatments in the Lick Creek Irregular Shelterwood study is now in preparation and fire hazard reduction is a consideration in treatment design.

Next steps: Further reduction in overstory basal area is required to maintain tree vigor in this cohort, to increase growing space availability for the second cohort, and to establish a third cohort (i.e., to shift the stand from a two-aged structure to a true uneven-aged structure). This treatment will again be an irregular shelterwood harvest, with SDI allocation used for stocking control. Additional treatments will also be required in the understory to reduce the presence of Douglas-fir in the second cohort and remove ladder fuels created by the growth of saplings and young trees adjacent to overstory trees.

Lessons learned—

- The 40–50 ft² basal area range was sufficient to regenerate a new cohort of ponderosa pine (although Douglas-fir also regenerated) while increasing the growth and resilience of older trees to drought, fire, and bark beetles.
- Removing shade-tolerant advanced regeneration before harvest is strongly recommended to prevent this cohort benefiting from increased growing space following harvest

and growing to a size at which the stems can withstand low-intensity prescribed fire. Mechanical treatment should be considered in situations where (1) prescribed fire presents a risk of overstory mortality, (2) advanced regeneration is of sufficient size that low-intensity prescribed fire will be ineffective, or (3) the intermingling of vigorous ponderosa pine regeneration with seedlings and saplings of less desirable species will likely kill otherwise healthy ponderosa pine.

- Retention of Douglas-fir in the overstory, even in relatively small proportions, can provide sufficient seed for Douglas-fir to dominate the understory. This is especially true where residual Douglas-fir are widely dispersed, and topography facilitates seed dispersal.
- The dry burn after harvesting had the most positive effect on ponderosa pine composition and fuel reduction of any of the three active treatment pathways in the Lick Creek Irregular Shelterwood.
- Whole-tree harvesting increases flexibility for prescribed burning, but retention of tops and limbs may create a fire hazard until these fine fuels decay substantially (which may occur within the first decade after treatment). However, distribution of these logging residues across the stand does increase surface fuel connectivity to carry prescribed fire on sites where few other surface fuels exist.

Primary literature sources used in this case study are Smith and Arno (1999), Smith (2000), Hood et al. (2020), and Tepley et al. (2020).

Lick Creek Demonstration-Research Forest: Single-Tree Selection Pathway

The single-tree selection transformation pathway (“Lick Creek Selection”) at Lick Creek Demonstration-Research Forest is the second of three experimental treatment pathways implemented at the site in the early 1990s (see the Lick Creek Irregular Shelterwood, above).

Site history and pre-treatment stand conditions—

The Lick Creek Selection unit includes trees of varying age, including some individuals approximately 400 years old at the time of treatment implementation, as well as much younger individuals that established during 20th century fire exclusion and as a result of past partial harvesting. Therefore, this treatment unit most closely resembles existing condition Type 5 (chapter 4). Consistent

with existing condition Type 5, trees of all age classes in the Lick Creek Selection unit were of low vigor and susceptible to drought, insects, and disease at the time of treatment implementation. Fire hazard was also high as a result of the dense multi-layered canopy structure.

Table 8.3—Summary data for the Lick Creek Selection site and harvest unit, as of 1991. Trees per acre, basal area and QMD apply to stems ≥ 1 inch dbh.

Site and pre-treatment stand summary, 1991	
Elevation (ft)	4,700
Habitat type	<i>Pseudotsuga menziesii</i> / <i>Symphoricarpos albus</i>
Age (years)	5 – 400+
Trees per acre	200
Basal area (ft ² ac ⁻¹)	110
QMD (inch)	10
Composition	Overstory: 90% PIPO, 10% PSME

Management objectives and desired future condition—

As above, for the Lick Creek Irregular Shelterwood unit.

Transformation sequence—

The planned transformation sequence called for immediate implementation of a modified single-tree selection silvicultural system that included prescribed burning. The structural objectives of selection harvests and burning included:

- increasing the vigor of the large pre-suppression era trees in the stand,
- reducing ladder fuels surrounding these pre-suppression era trees,
- increasing the distance between overstory tree crowns, and
- promoting rapid development of large (≥ 24 inch) trees.

Stocking control was planned using a modified BDq system, with residual basal area (B) set to 50 ft² per acre, maximum upper diameter (D) of 24 inches, with retention of scattered, larger old trees existing in 1991, and a q-factor of 1.2 using 4-inch diameter classes (i.e., 20% more trees in each successively smaller diameter class). This was supplemented with the creation of a small number of 1/4 to 1/3-acre gaps. A cutting cycle of 25–30 years was proposed for the selection harvests. Parts of the selection unit were managed using prescribed burning when fuel moisture was at intermediate

levels (30% duff moisture content), while other areas were not burned following selection harvest. Untreated “control” areas were also reserved for comparison against treated areas.

The first selection harvest in 1992 achieved the planned 50 ft² per acre residual basal area and reduced stand density to approximately 60 trees per acre. Most of the stand density reduction occurred in the smaller diameter classes. As with the Lick Creek Irregular Shelterwood, whole-tree harvesting with scattering of tops was used in efforts to balance reduction in activity fuels with nutrient retention.

Current conditions—

The Lick Creek Selection unit has made progress toward achieving the specified management objectives, but there are clear differences between areas in which prescribed fire was and was not used in conjunction with selection harvests (fig. 8.5). Regardless of whether fire was used or not, multiple cohorts are present, and the spatial pattern of vegetation is more complex than the “control” areas in which no harvesting was conducted. Canopy gaps created by the modified selection cutting have been particularly effective in diversifying structure, accompanied by the reductions in stand density from harvesting. The most notable difference between areas in which burning was used and those in which it wasn’t is the higher density and variation in sizes of seedlings, saplings, and small trees in areas with a “harvest and burn” treatment, compared to “harvest only” areas.



Figure 8.5—At least three cohorts are visible in and around this canopy gap (main image) in the Lick Creek Selection unit, 30 years after selection harvest and prescribed burning. By contrast, stand structure is much more homogeneous in an area of the unit that was left unharvested (inset image).

In areas treated with a combination of harvesting and burning, regeneration is abundant, especially in canopy gaps (fig. 8.6). Douglas-fir is common across all size classes in the regeneration and sapling layers. However, ponderosa pine regeneration is also common and relatively widespread, suggesting that it will be possible to recruit sufficient pine to eventually replace older cohorts, especially if the abundance of intermixed Douglas-fir is reduced in subsequent treatments.



Figure 8.6—Canopy gaps and lower stand density following selection cutting have stimulated recruitment in areas of the Lick Creek Selection unit treated with harvesting and burning. Douglas-fir is more abundant in the understory than stipulated in treatment objectives, likely due to retention of mature Douglas-fir during harvesting (for example, the bole in the foreground of the left-most image).

Seedlings, saplings, and small trees are also present in areas of the Lick Creek Selection unit treated with selection harvesting, but not burning, but at much lower densities. The appearance and location of this vegetation suggests that many of these saplings and small trees were advanced regeneration before the 1992 selection harvest, and Douglas-fir is more abundant in this layer than ponderosa pine. Instead, a relatively dense midstory composed of both ponderosa pine and Douglas-fir also exists in this “harvest only” area of the Selection unit, suggesting that increased growing space created by harvesting has benefited small trees established before cutting.

The observed differences in the structure of areas of the Lick Creek Selection unit that were treated with harvesting plus burning

and harvesting without burning suggest that burning may have improved seedbed conditions for regeneration and reduced the density of advanced regeneration existing at the time of selection harvest in 1992.

As would be expected from post-harvest growth of mid- and overstory trees over the past three decades, basal area in all harvest units now exceeds the 50 ft² per acre target (table 8.4). The next selection harvest is currently being planned and will again use a modified BDq diameter distribution for stocking control. This harvest will reduce stand density while preserving vigorous overstory trees.

Table 8.4—Current summary data for harvest units in the Lick Creek Selection study managed using transformation pathways involving harvesting only, and harvesting and prescribed burning. This data is for trees exceeding 4-inches dbh.

2022 stand structure	Harvest only	Harvest + burn
Trees per acre	73	52
Basal area (ft ² ac ⁻¹)	85	80
SDI (Imperial units)	126	116
QMD (inch)	15	17
Composition	PIPO 90%, PSME ~ 10%	PIPO 95%, PSME ~ 5%

Fire hazard metrics—

Data for evaluating fire hazard metrics for the Lick Creek Selection unit were only available for the most recent timepoint, an inventory conducted in 2022. Figure 8.7 shows simulated fire hazard using FVS, assuming severe fire weather, as shown in figure 8.3 for the Lick Creek Irregular Shelterwood unit.

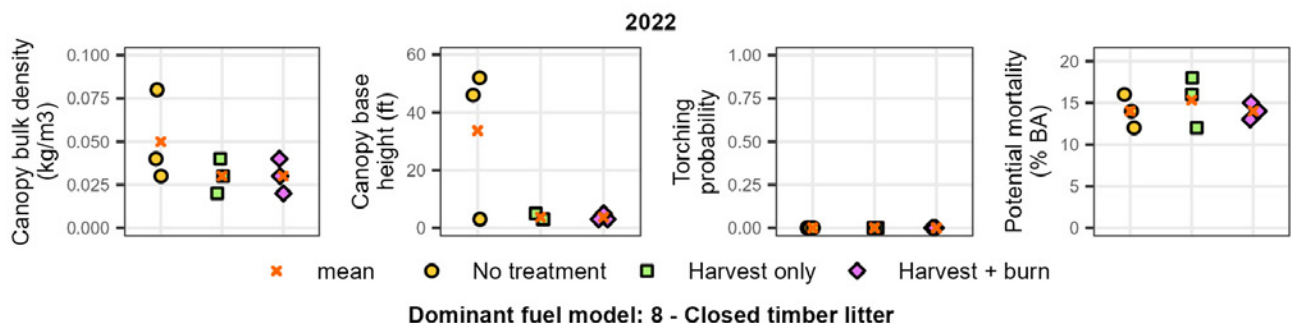


Figure 8.7—Canopy bulk density, canopy base height, potential mortality, and torching probability for forest in the Lick Creek Single-tree Selection Study managed using three alternative treatment pathways. Hazard metrics were calculated using FVS using identical specifications to those described in figure 8.4.

As of 2022, trends in fire hazard across the three treatment pathways in the Lick Creek Selection unit were indicative of similar post-treatment regrowth to that observed in the Lick Creek Irregular Shelterwood Study. While canopy bulk density remains lower in areas managed using harvesting with and without burning than in untreated areas, canopy base height is much lower in the actively managed areas. This is due to the growth of understory and mid-canopy vegetation over the decades after the selection harvests. Our analysis suggests that these changes in structure may contribute to slightly higher mortality in harvest only units than in untreated or harvest + burn units, with no differences between these latter treatment pathways.

The cause of the low projected torching probability in all treatment pathways is not known and may be an artefact of the simulation model. It is important to note that the FVS model used in these fire hazard simulations is not spatially-explicit (it does not take account of spatial pattern). This presents a particular problem for fire hazard assessment in the harvest + burn treatment pathway, as much of the regeneration in these units occurs in gaps, rather than below the overstory trees. This spatial distribution should result in lower fire hazard than a purely random distribution of understory vegetation.

Overall, the fire hazard metrics presented in figure 8.7 point to the need for a second harvest entry. This harvest is now planned and will seek to reduce fire hazard by managing the amount and spatial distribution of ladder fuels, along with other treatment objectives.

Next steps—

A second selection harvest is planned for the Lick Creek Selection unit and will be followed by prescribed burning for areas in the harvest + burn pathway. The specifications and goals of this treatment will be broadly consistent with the 1990s harvest entry. In the harvest + burn pathway in particular, this second entry will need to account for the ponderosa pine regeneration established following the initial harvest. In first-entry harvest gaps, ponderosa pine will require liberation from surrounding, and in some cases, overtopping, Douglas-fir saplings. In the harvest only pathway, selection harvest will now target the relatively dense and widespread midstory that presently occupies much growing space and creates an understory light environment that disfavors ponderosa pine.

Lessons learned—

- Prescribed burning following selection harvest appeared to improve conditions for regeneration on this site, compared to harvesting without burning (fig. 8.8).

- As with the Lick Creek Irregular Shelterwood, retention of even a relatively small number of overstory/mature Douglas-fir provided seed source for abundant Douglas-fir regeneration. For transformations in which restoration is an important management objective, retention of only the largest Douglas-fir—which provide important ecological functions—during harvest may be advisable. This will help avoid Douglas-fir dominating subsequent regeneration.
- The 1/4 to 1/3-acre gaps in this modified single-tree selection harvest were effective in recruiting ponderosa pine and will be particularly valuable additions to a standard single-tree selection harvest in stands with high stocking, limited spatial heterogeneity, and where overstory trees have narrow crowns. However, in the Lick Creek Selection unit, the presence of gaps did not guarantee strong regeneration, even in areas with plentiful seed sources (fig. 8.9).

Primary literature sources used in this case study are Smith and Arno (eds.) (1999) and Smith (ed.) (2000).



Figure 8.8—Abundant midstory trees exist in areas of the Lick Creek Selection unit treated with harvesting but not burning (a, b), but seedlings and saplings are less numerous than in areas treated with harvesting and burning in 1992. Ponderosa pine has not regenerated in all gaps in the harvest + burn units despite nearby mature overstory. The gap in (c) is a former skid trail, so soil compaction may be hindering establishment. However, this opening increases spatial heterogeneity and contributes to other management objectives.



Figure 8.9—A harvest gap created during single-tree selection harvest plus improvement cutting in a stand in the Frenchtown Face project. This relatively large (approximately 0.25 acre) harvest gap was created through the removal of only two overstory trees.

Multi-aged management on the Lolo National Forest

Managers on the Lolo National Forest in northwest Montana have been pursuing silvicultural transformation to multi-aged, pine-dominated structures at several sites. One such site is part of the Frenchtown Face project (fig. 8.9), located on the Ninemile Ranger District. The site is accessible, so it attracts many recreationists and has high public visibility. The Frenchtown Face single-tree selection is an example of the early stages of transformation from even-aged to multi-aged structure.

Site history and pre-treatment stand conditions—

The Frenchtown Face project single-tree selection units encompass more than 2,500 acres of predominantly low-elevation, gently sloping terrain in which dry forests in the *Pseudotsuga menziesii* habitat type series dominated by ponderosa pine were the primary cover type before Euro-American settlement. For a variety of

reasons, including fire suppression and historical logging practices, stands in the project area are heavily departed from the formerly dominant old-growth stage. Stand densities exceeding 150 ft² per acre basal area and 350 trees per acre are common, increasing tree and stand vulnerability to insects (notably bark beetles) and disease. Infilling of understories and midstories by Douglas-fir and other species with higher shade tolerance than ponderosa pine created ladder fuels that increased the risk of high-severity fire.

Management objectives and desired future condition—

Improving forest health was an important objective for the Frenchtown Face project single-tree selection units and was viewed as compatible with restoration of the assumed pre-settlement structure and processes, a second key objective. Restoration would also achieve other objectives, including improving terrestrial habitat for native species found in old-growth ponderosa pine forests.

The desired future condition for achieving these objectives is an uneven-aged stand with three or more age classes, lower stand density (target range 50–70 ft² per acre basal area), particularly in the understory, and ponderosa pine and/or western larch as the dominant tree species, depending on the site. The presence of snags, especially large snags, was desired for wildlife habitat. Maintaining recreational opportunities and aesthetic values during the transformation sequence were important intermediate management objectives.

Transformation sequence—

The transformation sequence for the Frenchtown Face project single tree selection units involves repeated single-tree selection harvests with prescribed burning, supplemented with improvement cutting during the initial stages of transformation. The latter was deemed essential prior to the first prescribed burn due to the high fuel loads and vertical continuity of fuels. Returning fire to the project area is, however, viewed as important to the ecological restoration objectives for stands in the project area and to maintaining lower fire risk in and adjacent to rural residential areas.

The first harvest entry occurred in 2012 and combined understory vegetation management and improvement cutting with a single-tree selection regeneration harvest. Harvest was followed, within two years, by a prescribed burn that attempted to improve seedbed conditions for ponderosa pine. Improvement cutting focused on shifting species composition from Douglas-fir dominance to ponderosa pine and western larch dominance via density reduction in stems less than 19-inch diameter, while understory

vegetation management had the same focus in stems below 5-inch diameter. These intermediate treatments were also designed to remove conifers near any aspen clones. Single-tree selection removed individual trees or small clumps, retaining conifers ≥ 19 -inch diameter (unless in conflict with other treatment objectives) and prioritizing trees with deep crowns and good form (likely to be vigorous and provide a good seed source) for retention.

Current conditions—

A small sample of stands included in the Frenchtown Face project were visited a decade after the initial harvest entry for developing this case study. These stands are now largely even-aged and single-storied. This is a short-term consequence of understory vegetation management and improvement cutting, which prioritized removal of smaller, younger stems in the understory and midstory.

Although this has simplified the vertical structure of the stand over the short term, retention of larger trees with deeper crowns is likely to benefit wildlife habitat and aesthetic values, consistent with management objectives. Also consistent with objectives, the stand is now dominantly ponderosa pine, with lesser components of western larch and Douglas-fir. Basal area is greatly reduced from pre-harvest levels, averaging 60–65 ft² per acre, but with considerable fine-scale spatial variability (range of 40–100 ft² per acre).

For stands that have only experienced one harvest entry and are largely even-aged, the spatial pattern (i.e., horizontal structure) of vegetation is already relatively complex. This is partly attributable to intentional incorporation of spatial variability into leave-tree marking and partly a consequence of some natural variability in the spacing of the largest trees in the stand, pre-treatment. In naturally regenerated stands, natural variability in tree location presents interesting opportunities for canopy gap creation during harvesting, such as the single-tree selection harvest that was conducted in these stands. Here, irregular tree spacing combined with relatively wide crowns on overstory trees enabled the creation of moderately-large gaps that provide high light conditions on the forest floor with the removal of only one or two overstory trees per gap.

Figures 8.9 and 8.10 give the impression that the first regeneration harvest in these stands was unsuccessful in establishing a new cohort of ponderosa pine, but closer inspection reveals many small, healthy seedlings, especially in harvest gaps (fig. 8.11). Most of these seedlings are young and likely established within the past three years. Stocking surveys conducted five years after the initial harvest and burn treatments would have concluded that these sites were inadequately stocked, but this masks a pattern of

delayed recruitment. This is a common phenomenon in naturally regenerated, unmanaged ponderosa pine stands due to the timing of cone development and seed dispersal relative to periods of favorable climate.



Figure 8.10—In these two stands, single-tree selection has built upon the irregular spacing of overstory trees, before harvest to reinforce a more complex spatial pattern, consistent with the restoration component of management objectives for the Frenchtown Face project.

Lessons learned—

- Combining selection harvest with improvement cutting can be an effective first step in a transformation sequence when initial stand conditions are highly departed from the desired future condition and conducting multiple independent harvest entries within a short period of time is not feasible.
- By working with and reinforcing any existing heterogeneity in the spacing of overstory trees, it may be possible to create relatively complex spatial structures in a single harvest entry without complex marking guides. This will be most effective in stands with low or moderate overstory density and is less achievable in dense, young plantations.
- Where possible, evaluating successful reforestation over timeframes longer than the standard five years post harvest is advisable. Even on relatively productive sites, seedling establishment may lag regeneration harvest and burning but then occur in sufficient density to achieve treatment objectives.



Figure 8.11—After an initial lag following harvest and prescribed burning, seedlings are beginning to establish in canopy gaps in these two stands in the Frenchtown Face project (highlighted in the yellow circles for smaller seedlings). Although young, this regeneration appears to be sufficiently widespread to eventually recruit into a viable second cohort.

This case study was prepared using detailed onsite conversation with management personnel, and the review of National Environmental Policy Act (NEPA) documentation (USDA Forest Service 2007) and silvicultural prescriptions provided by the Lolo National Forest.

Lubrecht Experimental Forest

The Lubrecht Experimental Forest, owned by the University of Montana, is one of the few remaining active sites within the Fire and Fire Surrogates (FFS) study (Bernal et al. 2025; Schwilk et al. 2009). The FFS sought to quantify the effects of alternative fuel reduction treatments on vegetation, fuels, and fire behavior. Fuel reduction treatments within the FFS included (1) prescribed burning (“burn only”), (2) a hybrid thinning (a treatment that combined some thinning with elements of selection harvest, simply referred to as “thinning” or “harvest only” from now on), and (3) a combination (harvest + burn) treatment. An objective of all treatments was to ensure at least 80 percent basal area survival of dominant and co-dominant trees during a fire burning under the 80th percentile weather conditions. Untreated control stands were also left for comparison purposes.

At Lubrecht, all treatments involving harvesting were also developed with long-term ecological restoration goals in mind. Harvesting was viewed as the first step in a longer treatment sequence that would eventually transform stands into uneven-aged structures resembling pre-settlement reference conditions from western Montana. Therefore, although implemented with fuel reduction as a primary initial objective, the thinning and combination treatments of the FFS study at Lubrecht are also the first stages of silvicultural transformation. We will focus on these two treatments in this case study. Primary literature sources used in this case study were Crotteau and Keyes 2020; Fiedler et al. 2010; and Hood et al. 2024.

Site history and pre-treatment stand conditions—

Lubrecht Experimental Forest is a mid-elevation site (4,150–4,550 ft) in the Garnet Range of western Montana. The sites are within the *Pseudotsuga menziesii/Vaccinium caespitosum* and *Pseudotsuga menziesii/Spiraea betulifolia* habitat types and were dominated by fire-tolerant ponderosa pine and western larch before Euro-American settlement.

In common with many forests in the northern Rockies, stands included in the FFS study were heavily cut over in the early 1900s, followed by gradual regeneration under a period of fire suppression. The resulting second-growth stands exhibited a mixed ponderosa pine–Douglas-fir composition. Basal area was only slightly above the estimated upper range for pre-settlement ponderosa pine stands in western Montana. However, an increasingly dense understory and midstory suggested that basal area growth would rapidly transition stands into the zone of competitive mortality and elevated susceptibility to bark beetles.

Fire hazard was already a concern due to the high loading of ladder fuels.

Table 8.5—Summary stand characteristics for the harvest and harvest + burn initial treatments at the Lubrecht FFS site. QMD, trees per acre and basal area are for stems $\geq$ 4-inch diameter.

Pre-treatment stand summary	Harvest only	Harvest + burn
Age (years)	80 – 90, very rarely up to 200	80 – 90, very rarely up to 200
QMD (inch)	11	11
Trees per acre	157	144
Saplings per acre	2690	2123
Basal area (ft ² ac ⁻¹)	89	90

Transformation sequence—

The generalized transformation sequence at Lubrecht will involve a combination of thinning, improvement cutting, selection harvests, and understory fuel treatments—both mechanical and prescribed burning. However, beyond the initial treatments implemented for the FFS study and a generalized intention to transition to selection-based regeneration harvests in the future, no firm transformation sequence has been detailed for the FFS stands at Lubrecht. Instead, the management strategy focuses on achieving uneven-aged structure through incremental steps, which are determined in response to changes in stand structure following the preceding treatment.

Although it has disadvantages, this “incrementalism” enables a high degree of responsiveness to actual stand development and to changes in environmental conditions, management capacity, and the wider societal context. This approach also forces managers to explicitly consider the most appropriate treatment to implement at any given point in time, rather than placing undue reliance on a treatment plan that may be out of step with stand development. This incremental approach may work well in some situations, but in many others, it is unlikely to be as viable. Incrementalism is particularly suited to forest management at Lubrecht because this site is extremely accessible, has a permanent staff, and is routinely visited by management personnel. The regular informal monitoring of stand conditions that occurs at Lubrecht permits less detail in advanced planning of when and what actions to take during the transformation. Below, we describe two of the four distinct transformation pathways implemented to date in different stands at Lubrecht.

Lubrecht Experimental Forest: Harvest Only Pathway

In 2001, stands in the Lubrecht FFS harvest-only pathway received a hybrid harvest treatment that included elements of commercial thinning, improvement cutting, and selection harvest. The marking targeted 48 ft² per acre basal area retention, preferentially in large (≥ 15 -inch dbh) ponderosa pine and western larch, followed by lodgepole pine and then Douglas-fir. In the understory and midstory, 250–370 healthy medium-sized ponderosa pine per acre were retained, where available, until reaching the target basal area. Non-merchantable material was not treated, but no attempts were made to avoid crushing this material during harvest operations.

As figure 8.12 illustrates, leave-tree marking before harvest achieved considerable heterogeneity in the spacing of residual growing stock, including creation of gaps and retention of small tree clumps. Targeting less-desirable species for removal also led to an increase in ponderosa pine dominance, and average tree diameter also increased. Increased growth rates over the decade following thinning resulted in increased resistance to threats such as drought and insects during this time. These changes all contributed to the restoration objectives of the transformation pathway.

From 2006–2012, stands at the Lubrecht Experimental Forest experienced an extended mountain pine beetle outbreak. Although all stands experienced some level of mortality, the bark-beetle kill was concentrated in unthinned stands (control stands and burn-only stands) in the FFS study. By 2022 however, regrowth among overstory and understory vegetation in all treatment pathways had increased overstory density and produced substantial ladder fuels (table 8.6).

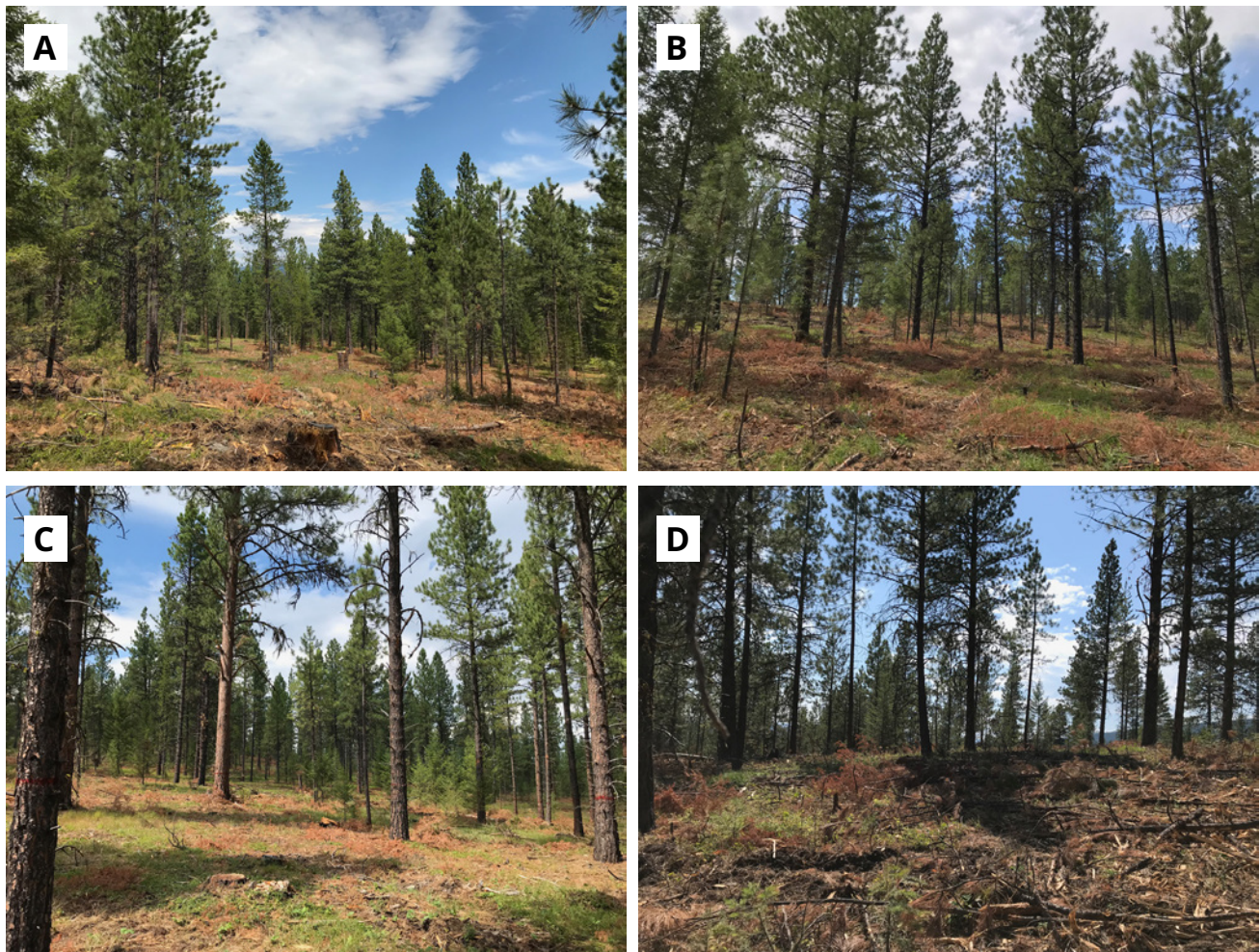


Figure 8.12—Recent harvest and mastication has created spatial heterogeneity in the overstory and a relatively open understory in the Lubrecht FFS harvest only pathway. Mastication has reduced understory ladder fuels and intentionally retained healthy ponderosa pine saplings (e.g., right middleground of image a, and left foreground on image b). Patches of Douglas-fir seedlings still exist in the understory, some retained in order to maintain species diversity and hiding cover (right rear ground of image c), although the quantity of Douglas-fir is greatly reduced compared to pre-mastication. The spacing of retained overstory trees following the 2001 harvest and 2023 commercial thinning varies across the stand, including creation of some modest gaps (image d).

Table 8.6—Stand summary data for the Lubrecht Experimental Forest harvest only and harvest + burn treatment pathways as of 2022, approximately 22 years after the initial treatment, and before the second harvest entry. With the exception of saplings per acre, figures relate to stems greater than 4-inches diameter at breast height.

2022 stand structure	Harvest only	Harvest + burn
Trees per acre	82	49
Saplings per acre	849	154
Basal area (ft ² ac ⁻¹)	75	57
SDI (Imperial units)	130	96
QMD (inch)	13	15
Percentage PIPO (%)	63	75

In 2023, a second-entry harvest and mastication treatment were implemented in response to the substantial overstory growth and accumulation of ladder fuels that had developed over the 22 years since thinning. The harvest was a combination improvement cut (further targeting removal of Douglas-fir and low vigor trees while improving spatial heterogeneity) and selection harvest (creating gaps to regenerate pine and larch) to a residual of 45 ft² per acre basal area. A goal of mastication was to reduce canopy fuel loads and fire hazard, but operators were instructed to retain low densities of healthy understory and midstory trees, with a preference for ponderosa pine. Douglas-fir was intentionally not eliminated in order to preserve tree species diversity.

Post-mastication vegetation and fuel inventories have not yet been analyzed, but site inspections indicate that the 2023 entry helped reinforce the pre-treatment overstory spatial pattern while reducing ladder fuel loads and creating growing space for retained saplings and small trees (fig. 8.12). Healthy ponderosa pine retained during mastication show promise for development of a second pine cohort, even though this was not the primary objective of the 2001 treatment, which had a strong fuel reduction motivation. While mastication is a more precise tool for controlling understory fuel loads than prescribed burning, some patches of retained Douglas-fir saplings are relatively dense and will likely require further treatment during the next cutting cycle. Additionally, in common with typical mastication treatments, it is likely that surface fuel loads, especially the 1-hr and 10-hr fuels that heavily influence fire spread, will be higher over the short term until decay processes appreciably reduce these fuels. This could happen within 10 years post-treatment in these relatively cool, dry forests containing decay-resistant species, but it is highly dependent on factors such as post-treatment weather conditions (Battaglia et al. 2010; Jain et al. 2018; Reed 2015; Wozniak et al. 2020).

Lubrecht Experimental Forest: Harvest + Burn Pathway

Stands in the Lubrecht FFS harvest + burn pathway received the same silvicultural treatments as the harvest only pathway (above), with the addition of a low-intensity spring prescribed burn in 2002. A second burn was implemented in 2024, and future sampling will examine the short-term effects of this treatment.

Changes in stand structure over the decades following treatment suggest that the harvest + burn pathway contributed toward achieving the restoration objectives as well as setting stands on the path toward the intended uneven-aged structure. Although the 2002 prescribed burn was generally low-severity, post-treatment overstory density was lower in stands receiving the harvest + burn first-entry treatment than in the harvest only stands, while

ponderosa pine dominance was higher. As with stands in the harvest only pathway, overstory growth rates increased stand density reduction, resulting in increased individual tree and stand resilience.

Twenty-two years after the first-entry burn treatment, a well-developed second cohort has established in the harvest + burn stands, despite cohort development not being a primary objective of the first harvest entry. Understory density is considerably lower than the pre-treatment density in 2001, thereby reducing fire hazard, but the proportion of ponderosa pine has dramatically increased. Pine regeneration in harvest + burn stands is widespread, sometimes occurring in clumps within canopy gaps, but also widely distributed as individual stems (fig. 8.13). Douglas-fir remains a substantial component of the understory, suggesting that future treatment will be needed to continue shifting understory dominance toward ponderosa pine.

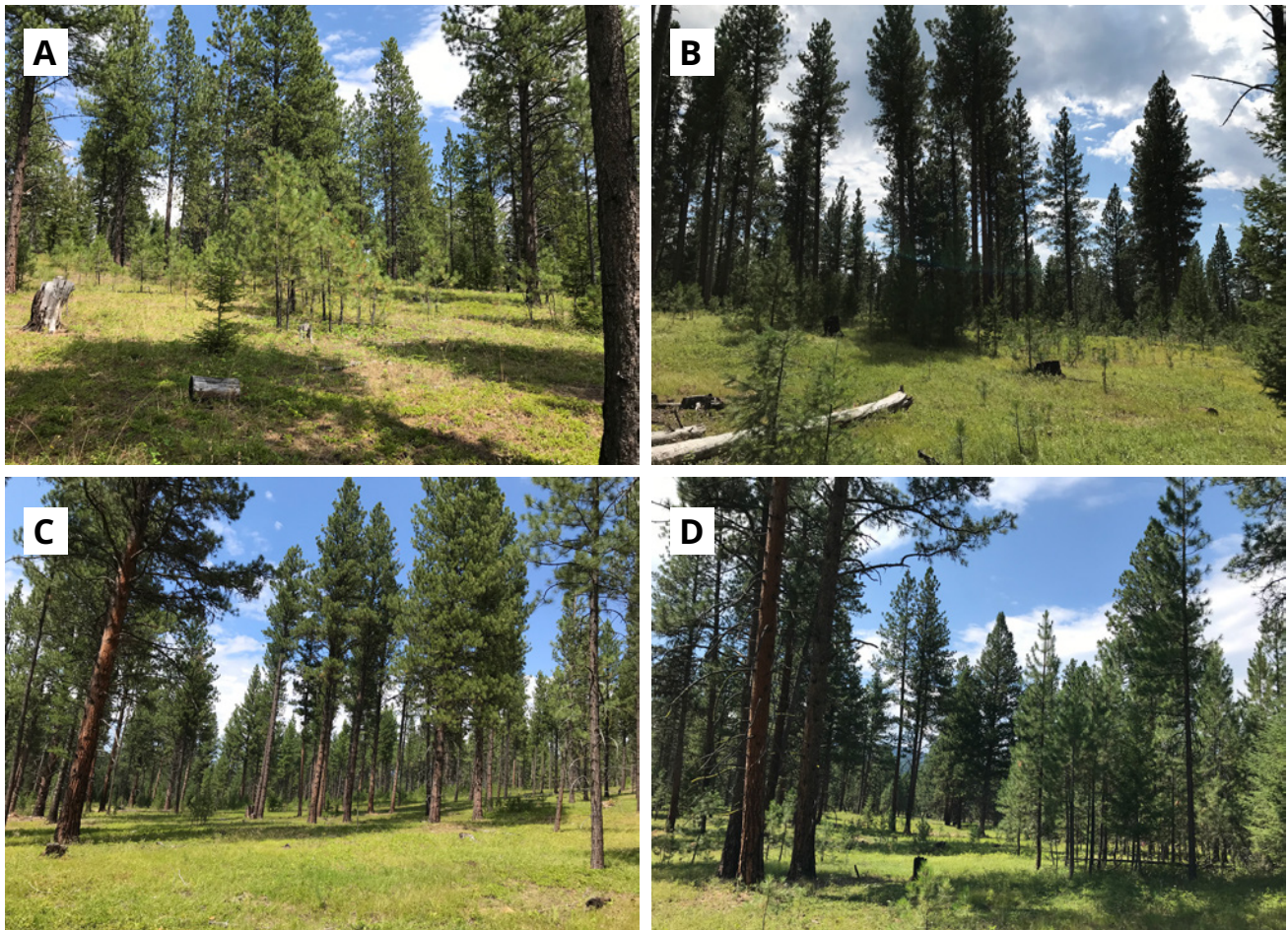


Figure 8.13—Ponderosa pine is relatively abundant in the understory of stands in the Lubrecht FFS harvest + burn pathway, and is distributed in clumps in harvest gaps (image a) as well more evenly dispersed as individuals (image b). The spatial structure of retained overstory trees includes the individuals, small gaps and openings that is characteristic of many pre-settlement, fire-maintained ponderosa pine stands and was used as a loose reference for this transformation sequence (images c and d).

As with the harvest only pathway, the harvest + burn stands received a second-entry harvest in 2023, again using a residual basal area target of 45 ft² per acre. Whereas stands in the harvest only pathway received a mastication treatment following harvest, stands in the harvest + burn pathway received a broadcast burn in the spring of 2024 to reduce surface fuels. The goals of this treatment were to (1) stimulate natural flora associated with forests with a frequent fire regime, (2) thin and release the cohort that regenerated following the prior overstory harvest, and (3) continue to transition tree species composition toward ponderosa pine dominance.

Fire hazard metrics—

Fire hazard metrics were simulated for stands in the thinning and cut + burn pathways of the Lubrecht FFS study, as described in the Lick Creek case studies. Figure 8.14, below, shows the estimated canopy base height, canopy bulk density, and potential mortality and probability of torching during severe fire events, for stands that received no treatment, as well as stands in the harvest only and harvest + burn pathways. Estimates are provided for 2002: 1–year post-treatment and 2022, the most recent inventory. Note that the latter inventory pre-dates the recent second-entry harvest and fuel reduction treatments.

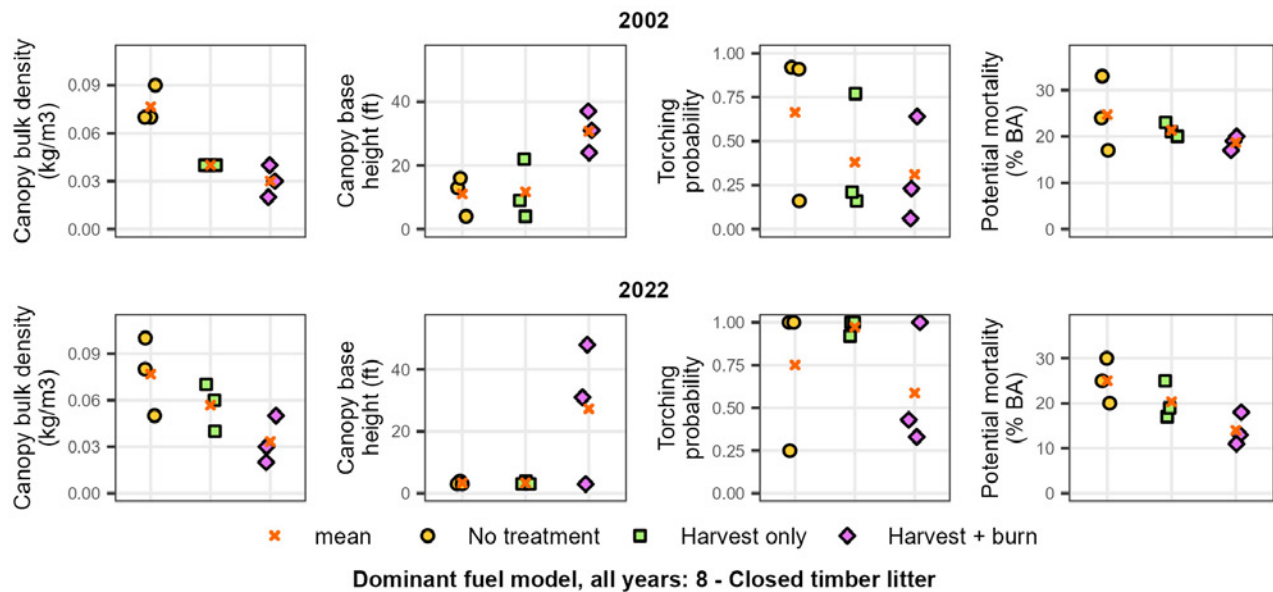


Figure 8.14—Temporal changes in canopy bulk density, canopy base height, potential mortality, and torching probability for forest at the Lubrecht Experimental Forest managed using three alternative treatment pathways. Hazard metrics were calculated using FVS using identical specifications to those described in figure 8.4.

Fire hazard reduction was a foundational management objective underpinning the transformation to multi-aged structures in the Lubrecht FFS study, and this is reflected in the fire hazard metrics displayed in figure 8.14. In 2002, one year post-treatment, canopy base height tended to be higher, and canopy bulk density, potential mortality, and torching probability tended to be lower in stands in the harvest only and harvest + burn transformation pathways than in untreated stands. As was the case at Lick Creek, the effect of harvesting plus burning on the fire hazard metrics that we examined was greater than that of harvesting alone. By 2022, two decades following the initial harvest entry, these same fire hazard metrics were indicative of lower fire hazard in stands in the harvest + burn pathway than either the harvest only pathway or in untreated stands. Unlike at Lick Creek, improved fire hazard outcomes for the harvest + burn pathway remain clear, two decades post treatment. These observations are broadly consistent with recent formal analysis of changes in fire hazard in the Lubrecht FFS study by Hood et al. (2024). A timeframe of 20 years post treatment is toward the outer edge of the expected duration of positive fire hazard reduction benefits from fuel reduction treatments in habitat types similar to those at Lubrecht Experimental Forest (Hood et al. 2020), underscoring the need for recent re-treatment of stands in the harvest only and harvest + burn pathways. Understory treatments—mastication and prescribed burning in harvest only and harvest + burn units, respectively—occurred recently. Visual inspection of the results (see photographs in figs. 8.12 and 8.13) of these treatments suggests that fire hazard is likely to be lower now than during the 2022 inventory, especially for the harvest only pathway.

Lessons learned—

- For sites that are accessible and regularly accessed by management personnel, an incremental approach to transformation can be effective in guiding structural changes. In this incremental approach, regular observation can help substitute for some of the long-term transformation sequence planning that is so valuable in stands that are infrequently visited.
- In common with observations at Lick Creek and findings from other studies, pairing harvesting with broadcast burning appears to be a more durable approach to managing fire hazard during transformation than harvesting alone. This is notwithstanding the effects of recent mastication (described below).

- Mastication treatments provide an alternative to prescribed burning (box 7) for achieving multiple silvicultural objectives. Initial observations from Lubrecht Experimental Forest suggest that modern equipment and skilled operators can achieve more nuanced, selective results than is often perceived possible. In turn, such treatments may also expand the utility of mastication beyond the realm of fuel reduction, to encompass other management priorities. This includes relatively fine control over understory tree (and, potentially, large shrub) species composition and spatial distribution to help direct structural development. In a transformation context, these effects of mastication may be useful when developing transformation sequences but may also have value as an adaptation tool when seeking to redirect structural development after unforeseen departure from the planned trajectory. At Lubrecht Experimental Forest, inventories over the next five to ten years will yield data to better understand the longer-term effects of such finessed mastication treatments on stand structure, fire hazard, and other management priorities.
- Consideration of the desired and probable location of ponderosa pine seedling establishment post-harvest is an important aspect of treatment design, but natural regeneration is difficult to predict. Ponderosa's requirement for relatively high light environments for survival and growth under most conditions warrants care in selecting harvest gap sizes, shapes, and locations (this can be informed by ecological theory, e.g., Larson and Churchill 2012). However, in the Lubrecht FFS study, especially the cut + burn pathway, spatial patterns of regeneration variously adhered to and departed from gap-based recruitment expectations. From a practical perspective, this highlights the importance of management flexibility, and the benefit of visiting sites before beginning detailed planning of each transformation treatment.

Lake Como Plantations

The Plantation case study at Lake Como in western Montana exemplifies a situation that is familiar to many managers in the northern Rocky Mountains, and which could be the poster child for transformation to multi-aged structures to meet the diverse objectives typical of public lands. This case study describes attempts to initiate transformation in dense, young stands originally planted with a primary focus on timber production. These efforts are only now beginning and will build off prior experimental treatments implemented for other purposes. Therefore, this case study illustrates how silvicultural legacies can be incorporated into transformation planning.

Site history and pre-treatment stand conditions—

The Plantation study is a 128-acre parcel of land located on the Bitterroot National Forest in the foothills of the Bitterroot Range. The site is on the northern shore of Lake Como, a popular recreation destination and is proximal to agricultural land and homesteads in the Bitterroot Valley. Although the site is mostly northeast- and east-facing, slopes vary from 5–40 percent and there is a 1,200 ft elevation gradient, resulting in a wide range of habitat-types.

The second-growth, ponderosa pine-dominated forest that existed on this site was harvested and replanted between 1988 and 1991, before the inception of the Plantation study. In effect, these harvests most closely resembled clearcut or clearcut with reserve treatments, with low but variable levels of overstory retention across the 13 units on the site. At the most recent inventory, basal area of the residual trees locally reaches 80 ft² acre⁻¹, but 40 ft² is more typical across the site, and although ponderosa pine dominates, mature Douglas-fir are also present.

After harvesting and a subsequent broadcast burn, ponderosa pine was planted at an 8 x 8 ft spacing. As the overstory basal area is concentrated in large, scattered individuals, the stands were essentially even-aged (see table 8.6 for stand summary data for the planted cohort).

By the inception of the Plantation study in 2004, the young forest at Lake Como was extremely dense, prompting concerns about vegetation health. As these plantations age and diameters increase, maintaining high stand densities would expose the trees to risks from bark beetles. Additionally, despite ponderosa pine's resistance to many fungal pathogens, *Elytroderma* needle blight (caused by the fungus *Elytroderma deformans*) can significantly reduce productivity, and is therefore a concern for planted stands managed for timber production. This provided the motivation

for a study on silvicultural approaches to reduce *Elytroderma* susceptibility that subsequently became an effort to transform these young even-aged plantations to an uneven-aged structure.

Table 8.7—Summary data for the Lake Como Plantation site and stand structure before treatment in 2004. Trees per acre accounts for all stems above 1 ft in height, and excludes scattered residual overstory trees.

Site and pre-treatment stand summary, 2004	
Elevation (ft)	4,600 – 5,800
Habitat types	<i>Abies grandis</i> / <i>Clintonia uniflora</i> , <i>Pseudotsuga menziesii</i> / <i>Symphoricarpos albus</i> , <i>Pseudotsuga menziesii</i> / <i>Vaccinium globulare</i>
Age (years)	15
Trees per acre	500 – 580
Composition	Dominantly planted ponderosa pine, with minor components of naturally regenerating Douglas-fir, grand fir, lodgepole pine

Management objectives and desired future condition—

The stands at Lake Como were originally planted with a primary focus on timber production. This has now shifted under the current multi-objective paradigm on public lands, and the current objectives particularly emphasize resilience to insects and pathogens, and lowering fire risk. Sustaining some level of timber production remains an objective. Additionally, given the proximity to highly trafficked recreation sites and local communities, aesthetics are now a management consideration to an extent that was not the case when the sites were clearcut and plantations established.

An uneven-aged structure with much lower stand densities (100–200 trees per acre across all diameter classes, depending on site aspect) than existed at the inception of the Plantation study is the desired future condition. In this future condition, ponderosa pine is the dominant species in all canopy layers, and maintaining a population of large ponderosa pine (target of 40–80 ft² per acre) at all times is important. A heterogeneous, gap-based spatial structure is envisaged. Small numbers of large pine snags are also attractive for habitat function.

Transformation sequence—

The sequence of treatments that eventually became a transformation sequence began in 2004 with two experimental harvests designed to reduce *Elytroderma* susceptibility. Stands were pre-commercially thinned to either a 12 x 12 ft or 18 x 18 ft spacing, retaining the most vigorous individuals and specifying a target 25 percent variability in spacing to marginally reduce the regularity of

the pre-existing plantation grid. These treatments reduced stocking to 302 trees per acre in the 12 x 12 ft spacing units and 134 trees per acre in the 18 x 18 ft spacing units. Young ponderosa pines were pruned to half of the live crown.

All Douglas-fir greater than 10-inch dbh that were infected with mistletoe were girdled. Meanwhile, Douglas-fir, grand-fir, and lodgepole pine natural regeneration in the understory was slashed.

These treatments were not implemented with the goal of transformation to uneven-aged structure. When the *Elytroderma* study ended in 2014, the stands became a target of research into the effects of mountain pine beetle on young stands, as western Montana was then suffering a major beetle outbreak. In common with the Lubrecht Experimental Forest case study, an incremental approach will now be used to shift these stands to the desired uneven-aged structure.

Current conditions—

The initial spacing trials successfully reduced stand density of the planted ponderosa pine cohort. This was aided by bark beetle mortality. Recent growth rates for this pine cohort are high. Despite this, this cohort is now approaching full canopy closure and future growth rates are likely to decline. Spacing of this cohort is less regular than the original planting grid, helped by natural mortality over the past decade and variability in site quality (fig. 8.15). Further, reductions in density have also promoted a locally-variable shrub layer that increases compositional and structural diversity and improves habitat quality. Yet, these stands are very far from the irregular, gappy structure characteristic of pre-suppression-era, unmanaged ponderosa pine stands (fig. 8.15).

Residual overstory trees are now large, act as good seed sources, and would be highly resistant to fire when they are not surrounded by younger trees (fig. 8.15). Mortality caused by western pine beetle has produced the desired population of large-diameter snags. However, girdling of larger Douglas-fir was not as successful as envisaged (fig. 8.15). This has had repercussions for understory composition in all harvest units, irrespective of the 2004 spacing treatment.

Natural regeneration of Douglas-fir from seeds supplied by retained overstory trees and trees in the surrounding forest stimulated the regeneration of a new cohort beneath and around the planted ponderosa pine (fig. 8.15). Ponderosa pine natural regeneration is also present at lower densities, supplemented by lodgepole pine and grand fir from surrounding seed sources. A 2020 inventory recorded stand densities among stems ≥ 1 ft height but < 12 -inch dbh that ranged from 925 trees per acre (TPA) for

Douglas-fir, 150 TPA lodgepole pine, 100 TPA ponderosa pine, and 50 TPA grand fir, to 1,575 TPA Douglas-fir, 375 TPA ponderosa pine; 200 TPA grand fir, and 50 TPA lodgepole pine. Distribution of this understory vegetation is patchy, with considerable local variations in stem density. Although dead surface fuel loads remain low in all units (0–5 tons per acre), this new conifer understory now poses a major fire hazard and is also reducing available resources for the planted ponderosa pine cohort and the scattered residual overstory trees.

Future transformation steps—

The primary concerns for designing the next steps in the transformation sequence for these stands are:

- The presence of a locally-dense understory cohort dominated by species that are more shade-tolerant than ponderosa pine.
- The presence of scattered residual overstory Douglas-fir that have proven to be effective seed sources for ongoing recruitment in the understory.
- Limited spatial variability and higher stocking in the planted ponderosa pine cohort than desired for the stated management objectives.

The planted ponderosa pine cohort provides the primary building blocks for the future uneven-aged stand so initial treatments must aim to secure and develop this layer. The large, residual overstory pines are a valuable contributor to structural and habitat diversity, and an important seed source. They will be maintained throughout the transformation treatments over the medium term.

The next steps in the transformation sequence will involve a regeneration harvest to (1) reduce stand density in the planted pine cohort and (2) increase spatial heterogeneity by expanding on the limited spatial heterogeneity that developed after the 2004 precommercial thinning. This strategy was used effectively in the case study on *Multi-Aged Management on the Lolo National Forest* elsewhere in this chapter. To be successful, this regeneration harvest must be accompanied by an understory treatment that substantially removes the existing dense, Douglas-fir-dominated understory. A carefully controlled prescribed burn is the best candidate for this because the understory cohort remains small and lacks fire resistance, and the planted pine cohort was pruned to increase canopy base height. Any planted ponderosa pines with low crowns and those that have understory conifers within their dripline are relatively vulnerable to the prescribed burn and could also be targets of the next regeneration harvest.

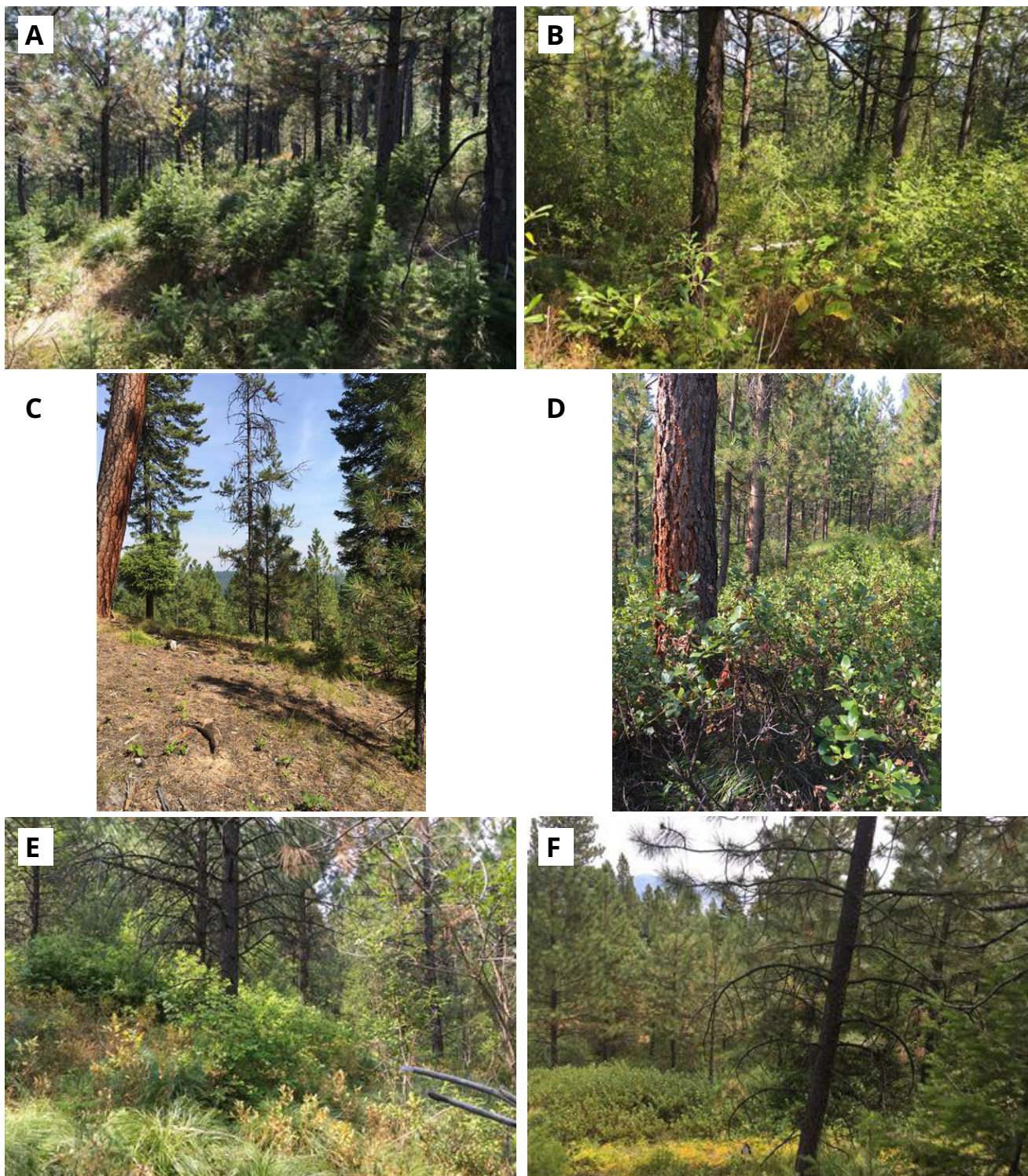


Figure 8.15—A new cohort has established in the understory of the former plantation at Lake Como, and is predominantly Douglas-fir (images a, b). However there is considerable spatial variability in understory density. Understory vegetation is most sparse on the harshest sites (e.g., c). Scattered residual overstory pine (left, image c) retained during the 1988 harvest are now large and fire-resistant, but some residual mistletoe-infected Douglas-fir that were girdled in 2004 have survived (background, image c) and contribute seed for new cohort establishment. In some areas, the regular spacing of the former plantation remains apparent (d). In other areas, pre-commercial thinning in 2004, pockets of shrubs, and variability in site quality have increased spatial heterogeneity from the original plantation (e, f), and provide a structure for future regeneration harvests to build around.

On the drier portions of the Plantation study site, low-level mortality of individual trees from bark beetles may still occur over the time until these stands are of merchantable size and ready for a regeneration harvest. Monitoring will be required to identify any such mortality and develop silvicultural responses.

Managing the low density of residual overstory Douglas-fir will be a challenge. As with the residual ponderosa pine, these Douglas-fir are an excellent source of structural and habitat diversity, are relatively resistant to fire, and provide a host of other ecological functions. Retaining a small population of species other than pine also increases compositional diversity, which has benefits for habitat quality. Yet, seed rain from these trees will continue to establish in the understory, threatening to shift the stands away from pine-dominance, as well as homogenizing spatial structure and contributing to fire hazard. Given (1) the relatively low number of these large, residual Douglas-fir, and (2) the presence of Douglas-fir in the surrounding forest irrespective of treatments within the stands, the best strategy over the short-term is to retain the existing overstory Douglas-fir, follow up any regeneration harvests with prescribed burns, and utilize improvement treatments as necessary to control understory composition.

Lessons learned—

- The 2004 pre-commercial thinning was not designed to achieve transformation to a multi-aged structure. However, it is likely that wider spacing (e.g., 30 x 30 ft), combined with more prescribed variability in retention would have helped set these stands on a better path to uneven-aged structure.
- Felling the mistletoe-infected residual overstory Douglas-fir and retaining the boles on-site, instead of girdling, would have reduced within-stand Douglas-fir seed sources while providing valuable coarse woody debris (currently deficient in these stands).

Chapter 9: Additional Considerations for Multi-Aged Management

While this guidebook is not intended as a comprehensive text on multi-aged management, there are many practical consequences of transformation to multi-aged structures that merit further elaboration. In this chapter we discuss issues that are particularly relevant to the design of silvicultural treatments in ponderosa pine stands during and after transformation. We provide ideas to inform management implementation, but the primary intent of this chapter is to encourage explicit consideration of each of the following topics when designing treatments as part of the transformation sequence and when evaluating whether transformation to a multi-aged structure is appropriate in a given circumstance.

Fire hazard

Background—

As described in chapter 1, frequent to moderately frequent low-severity fire was essential to maintaining ponderosa pine as an important component of forests and open woodlands in large areas of the northern Rocky Mountains before Euro-American settlement (Fiedler and Arno 2015). Ponderosa pine's dominance in these frequent-fire conditions owes to the many physiological and morphological adaptations that confer greater fire resistance than any associated tree species except western larch (Fryer et al. 2018; Stevens et al. 2020). Suppression of fire over the past 150 years has eroded this competitive advantage of ponderosa pine by creating fuel loads and fuel structures that are conducive to the kind of high-intensity crown fires that overcome even the most fire-tolerant species (e.g., Arno et al. 1997; Hagmann et al. 2021). As fire behavior and effects are linked to fuel structure (e.g., Agee 1996; Rothermel 1983), transformation to multi-aged structure has implications for fire hazard management. Fortunately, stand structure is a variable that forest managers have considerable control over, and while some multi-aged structures may increase certain components of fire hazard, other components of fire hazard may be minimized in multi-aged structures, or are independent of age-class structure.

At the scale of individual forest stands, resilience to fire—i.e., the capacity of the stand to withstand fire disturbance without fundamental change in ecosystem structure and function—hinges on the persistence of live vegetation and/or seed sources. Persistence of a proportion of pre-fire, live basal area through disturbance events preserves key ecosystem functions such as growth, nutrient cycling, and habitat provision, and, critically,

At the scale of individual forest stands, resilience to fire hinges on the persistence of a proportion of live vegetation and/or seed sources through disturbance events.

provides a seed source for regeneration of future cohorts. In dry forests, including ponderosa pine, four principles that promote stand-scale fire resilience are (1) reduce surface fuels; (2) increase height to live crown; (3) decrease crown density; and (4) keep large trees of fire-resistant species (Agee and Skinner 2005).

Multi-aged structures may present conflicts with a number of these principles of fire resilience, but thoughtful management can defray some of these concerns. Maintaining low surface fuel loads (principle 1) is more challenging in multi-aged than even-aged stands because of the necessary presence of seedlings and saplings in the understory during some or all of the cutting cycle. These saplings and small trees also act as ladder fuels, reducing the gap between surface and crown fuels, counter to the intent of principle 2 (increase height to live crown). Two-aged structures will minimize these sources of fire hazard compared to uneven-aged structures, because (1) the age (and size) gap between cohorts typically exceeds that in uneven-aged structures and (2) because both cohorts in two-aged stands occupy midstory or overstory positions (creating a fuel gap between forest floor and canopy layer) for a significant proportion of the cutting cycle.

Hence, on sites where fire hazard is a primary management concern, two-aged structures may provide more opportunities for success without adding significant management complexity compared to uneven-aged structures. Where uneven-aged structures are preferable for other reasons, exercising more control when designing the spatial pattern of harvesting and overstory retention provides a means of limiting fire hazard (see recommendations below), as do mechanical fuel treatments. Therefore, while surface and ladder fuels are certainly complications for multi-aged management, it is possible to minimize their influence on fire hazard.

In other respects, multi-aged structures often contribute to fire resilience (fig. 9.1). Crown density (fire resilience principle 3) is high in most plantations and former plantations that are the target of transformation to multi-aged structures. Although crown density is not necessarily related to age-class structure, multi-aged structures in ponderosa pine stands will tend to emphasize lower crown density and more heterogeneous canopy bulk density than in even-aged stands. This is because of the need for relatively high understory light levels to establish and grow new cohorts.

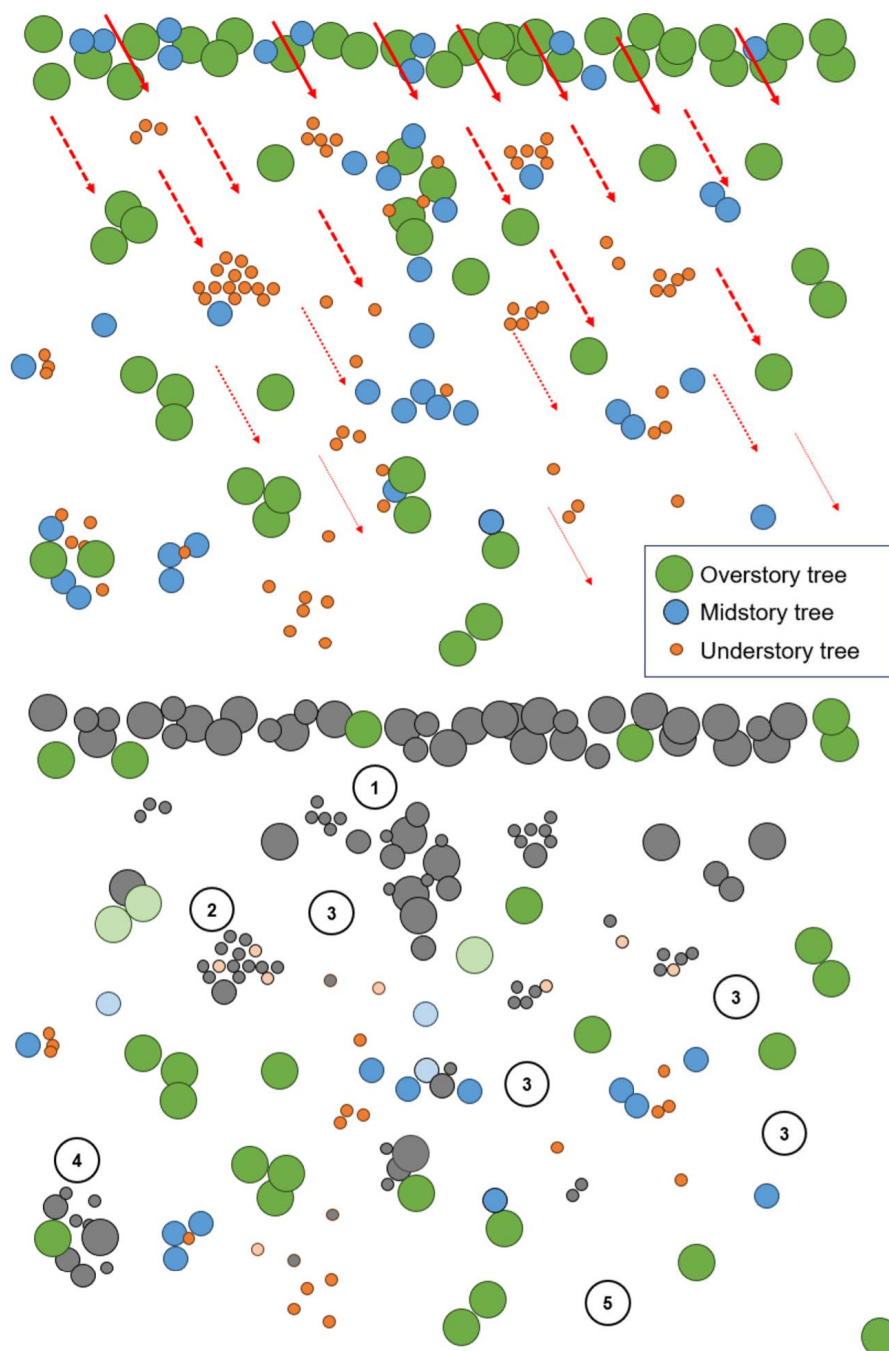


Figure 9.1—A fire burning into a multi-aged stand may kill some individuals in each cohort without harming other individuals. In this example of an active crown fire spreading into a multi-aged stand from a denser even-aged stand (solid red arrows in the top image), overstory mortality occurs where understory vegetation underneath or immediately adjacent to the overstory creates vertical fuel ladders (circles 1 and 4). Fire thins out dense pockets of saplings and seedlings (2), but lower fuel loads in gaps may cause lethal crown fire to transition to a lower-intensity surface fire (3). After this happens, mortality of understory (5) and overstory (4) vegetation will be patchy, and controlled by factors such as localized topography and fuel loads.

As with even-aged structures, different multi-aged structures may have higher or lower fire hazard.

Multi-aged ponderosa pine stands also score well on the principle of retaining large, fire-resistant trees (fire resilience principle 4). As multi-aged ponderosa pine-dominated stands never enter the early stand development phase, as do even-aged stands, a proportion of the growing stock will be maintained in size classes that have moderately high to high fire tolerance. Multi-aged structures also facilitate the retention of trees to very large sizes and old ages, whether through isolated retention of specific individuals or by extending the desired maximum age of the oldest cohort. As is the case in even-aged stands, different multi-aged structures may have higher or lower fire hazard depending on their structure. Silvicultural practices can minimize the inherent weaknesses of multi-aged structures and emphasize the attributes that do confer fire resilience.

One additional concern about fire in multi-aged silvicultural systems is the extent to which multi-aged structures limit management freedom to implement prescribed burning for fuel reduction purposes. Prescribed burning is a useful tool for (1) reducing surface fuels to achieve fire hazard reduction objectives, (2) preparing mineral soil seedbeds for regenerating new cohorts, (3) regulating regeneration density to achieve desired levels of recruitment, and (4) maintaining overstory vigor and resistance to climate-disturbance stressors by reducing competition for resources. In multi-aged stands, concerns exist about the risk to younger cohorts from using prescribed fire, as well as safety concerns over the possibility of ladder fuels enabling surface fires to spread to tree crowns (O'Hara 2014).

Although concerns about the fire hazard associated with prescribed burns in multi-aged stands are not unreasonable, there are options (described below) for controlling risk while achieving beneficial outcomes. Sometimes these actions will include mechanical treatments in conjunction with fire, such as targeted understory vegetation management or in the case of fire-excluded stands containing old trees, targeted removal of thick duff layers around the bases of larger and older trees. In other situations, careful design of vegetation structure during and after the transformation process can ensure that prescribed fire can be used—and may be an essential tool—in multi-aged systems. And in those situations where prescribed fire is unlikely to achieve objectives for a given level of risk, mechanical treatments can provide some of the benefits of prescribed fire. Mechanical treatments have their own advantages when attempting more precise regulation of understory density, composition, and spatial distribution.

In summary, there are risks associated with the use of prescribed fire in multi-aged stands, but these risks can typically be mitigated

by treatment design and implementation or sidestepped by using mechanical alternatives.

Implementation ideas—

Many existing publications provide recommendations for managing wildland fire hazard (including fuel reduction), using prescribed fire as a silvicultural tool, and landscape-scale applications (e.g., Hood et al. 2022; Jain et al. 2012; North et al. 2021; Tubbesing et al. 2019; York et al. 2021). Therefore, discussion below is limited to ideas that are particularly relevant to multi-aged stands and the transformation to multi-aged structures.

- Use site productivity and fire histories developed for sites that are similar to the target stand to inform the development of a desired future condition and cutting cycle that align with expected natural fire frequency for the site. This can help ensure that the silvicultural system for the stand is not fighting against the biophysical tendencies of the site. For example, maintaining uneven-aged structures will require more management effort, for a given level of fire hazard, on productive sites than on low-productivity sites.
- When designing the desired future condition and planning the transformation to multi-aged structure, explicitly consider the spatial relationships between (1) vegetation in different canopy layers (and different age classes) and (2) vegetation and physical site attributes likely to influence fire behavior. Doing so forces intentional assessment of fire risks in the context of management objectives for the site and other resource constraints.
- Irrespective of the desired future condition, management actions should generally seek to minimize vertical fuel continuity created by the location of younger cohorts immediately beneath or adjacent to older trees (Churchill 2021). Horizontal separation of cohorts of different sizes minimizes the potential for torching and active crown fire spread during fire events and creates fuel structures conducive for using prescribed fire (i.e., pyrosilviculture; North et al. 2021; York et al. 2021). When horizontal separation between the canopy layers exists, low-intensity prescribed burning can be an effective, low-risk method of controlling seedling densities in gaps as part of stocking control procedures. Horizontal separation of younger and older cohorts is most easily achieved using aggregated retention patterns in two-aged stands and area control methods of growing stock regulation in uneven-aged stands.

- Creating large canopy gaps in group selection systems and removing of small clumps of trees rather than individual trees in single-tree selection systems can also increase opportunities to achieve horizontal separation between cohorts. Mechanical treatment of understory vegetation can achieve relatively precise control over the spatial relationship of different cohorts, but does not solve the issue of heavy surface fuel loads.
- Thinning is an effective tool for managing canopy bulk density. It can be combined with regeneration harvest entries to alter crown fire hazard throughout the stand without requiring additional harvest entries. Combining thinning with regeneration harvest is especially useful when regeneration harvest activity is focused on discrete areas of the stand—thinning is the tool for controlling density outside of the areas affected by regeneration harvest.
- Careful consideration of ignition patterns, methods, and fuel moistures during prescribed burns can help maintain desirable patches of regeneration and create new growing space to maintain multi-aged stands.
 - Spring burns typically create more heterogenous patterns of vegetation survival than fall burns due to higher surface fuel moistures. Fall burns can still reduce fuel loading while maintaining a viable population of existing regeneration by implementing the burning after a sufficient density of ponderosa pine saplings have attained sizes able to withstand low-intensity surface fire.
 - The choice of ignition patterns can influence fire effects on vegetation. Drip-style ignition is more likely to produce a patchy mosaic of burned and unburned vegetation than continuous strip fires and is better suited to preserving regeneration in specific locations. This may be especially useful during fall burning in fuels with consistent, relatively low fuel moisture.
 - Aerial ignition does not allow fine-scale targeting of individual regeneration patches for retention, but heterogeneity in vegetation survival can be altered by adjusting the ignition grid density and pattern across large units. This allows for a balance of fuel and fire hazard reduction while also improving the survival of planted trees and natural regeneration.

- Aerial ignition is compatible with transformation of plantations embedded in large prescribed fire units. During aerial ignition of units that contain embedded younger plantations, reduce lighting density or do not light within the plantation and then resume the normal lighting outside of the plantation. This will increase survival of planted trees, while allowing the fire to burn into the plantation. Where feasible, consider precommercial thinning of plantations, especially on the downslope sides, prior to aerial ignition. This can help reduce fire intensity along the downslope side of the plantation boundary and encourages patchy, surface fire throughout the remaining portion of the plantation.
- Discussing fire effects objectives with the burn crew prior to the burn and having good communications with lighters during the burn so they can quickly adapt and alter ignition patterns is essential. Training burn crews about fire ecology should improve burn outcomes so that burn crews understand how fire behavior can achieve desired fire effects.
- The risk-reward balance from prescribed burning can be adjusted by careful timing of burn operations relative to regeneration harvests. In most situations, conducting burns at the end of the cutting cycle—i.e., just before or after a regeneration harvest—coincides with the point in the cutting cycle at which the youngest cohort in the stand is at its oldest (before a new “youngest” cohort is established). This should maximize survival rates of this cohort, while also creating the mineral soil seedbed that is favorable for ponderosa pine establishment. When prescribed fire is being used to shift the composition of a mixed-species understory toward ponderosa pine, conducting burning when the understory is of large sapling to small pole size (typically less than 30 years old) should maximize opportunities to selectively kill Douglas-fir and/or grand fir (Rodman et al. 2021). It is at this size that the difference in fire tolerance between ponderosa pine and these other species is greatest.
- Combining prescribed fire with small amounts of mechanical fuel treatment can be an effective strategy in stands where pockets of vertical fuel continuity exist but are not the norm. For example, in gap-based treatments where discrete clumps of seedlings or saplings exist adjacent to, or below, gap-edge trees, mechanical removal of these small areas

of higher fire hazard can enable subsequent prescribed burning of the entire stand.

- Creating small openings that are permanently maintained as mosaic-meadows (Matonis and Binkley 2018) can help in fire risk management as well as supporting other ecological functions. Matching the location of these openings to site conditions that do not favor tree regeneration (e.g., poor soil, exposure to wind and/or high temperature) minimizes lost production and committing resources to poor microsites.
- Designating at least a small proportion of trees for retention to old-growth ages, irrespective of the average age of the oldest cohort in the desired future condition, increases the potential for continuity of seed sources. As these trees age and develop the characteristics of old age (e.g., extremely thick bark and high crowns) they will become structural anchors that provide resilience in the event of fires that exceed the tolerance of younger (often smaller) growing stock. Designating these reserve trees before they reach older ages allows ongoing management (e.g., radial thinning) that reduces resource competition to, and maintains the vigor of, these individuals throughout their development.

Like many aspects of silviculture, decisions at the stand scale are nested within the wider context of landscape-scale planning. Stand-scale decisions about the appropriate multi-aged structures for managing fire risk should account for the larger landscape planning environment and factors operating at the meso-scale (i.e., larger than stands but smaller than landscapes) (e.g., Hood et al. 2022; North et al. 2019). For example, the effectiveness of stand-scale fire hazard reduction may be reduced (but not eliminated) if the stand is exposed to severe fire spreading from adjacent fire-prone areas with high fuel loads. By contrast, multi-aged stand structures that present relatively high fire hazard—such as multi-layered, uneven-aged stands managed using single-tree selection—but provide high benefits for other objectives, may be acceptable in inaccessible areas far from the WUI.

Wind hazard

Background—

Ponderosa pine is more windfirm than many associated species in the northern Rocky Mountains, but the risk of windthrow may be an important consideration on some sites. Compared to grand fir and, to a lesser extent, Douglas-fir, ponderosa pine has a competitive advantage in windy areas because it can develop a taproot to soil depths of 6 ft (or considerably more if bedrock cracks permit) (Oliver and Ryker 1990). However, windthrow may still cause mortality (Johnson 1966), particularly on sites that are topographically exposed or where shallow, poorly drained, or clay-rich soils inhibit downward root penetration.

Silvicultural practices that influence stand structure may mitigate or exacerbate the biophysical windthrow hazard on a given site by altering the amount of wind stress to which trees are exposed (Ruth and Yoder 1953). For example, hard boundaries at the edges of large clearcuts increase windloading and windthrow risk for edge trees when wind blowing off the clearcut is forced over the canopy (British Columbia Ministry of Forests 2003). By contrast, silvicultural practices that gradually expose trees to more wind stress, such as repeated thinning, may induce physiological adjustments that increase windfirmness over time (O'Hara 2014) (fig. 9.2).

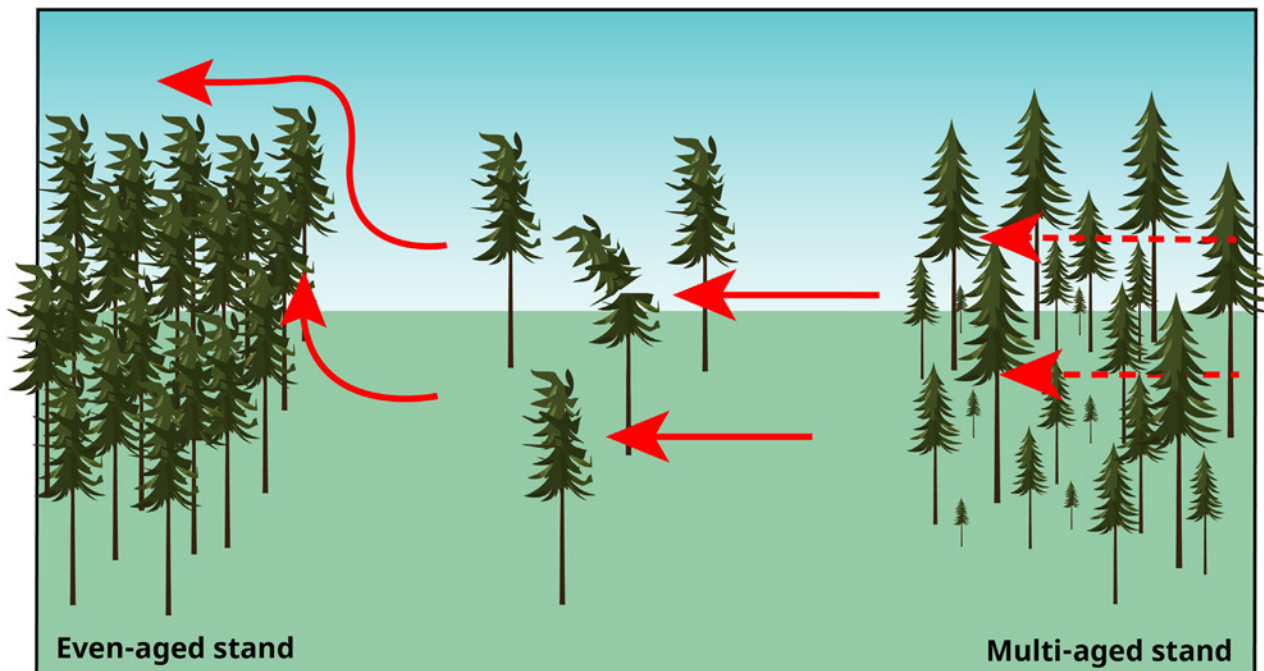


Figure 9.2—Hard boundaries and dispersed individuals may present higher windthrow risk than complex canopies. Knowledge of these differences can be used to tailor multi-aged stand structures and harvest methods to site-specific wind exposure.

The transformation from even-aged to multi-aged structure may present similar forms of windthrow risk to those experienced when executing a thinning or a conventional shelterwood or seed-tree regeneration harvest. Windthrow is a risk when trees that are accustomed to closed-canopy conditions with low wind exposure suddenly transition to conditions of much higher wind stress. These risks are most acute during the early stages of transformation from a dense even-aged stand (e.g., a plantation), as these trees often have (1) a high height-to-diameter ratio, an attribute that is inversely related to stability, and (2) a restricted lateral root system that is often constrained to the width of the tree crown (O'Hara 2014). Risks are likely lower when transforming a stand in which mature overstory trees developed at lower stand densities.

Over the long term, transformation from even-aged to multi-aged structure may reduce windthrow risk, but this depends on the type of multi-aged structures and the practices that are employed. Windthrow risks in uneven-aged stands managed using selection systems are often relatively low. This is because such stands typically have relatively complex canopy structure and small harvest gaps instead of the large openings and hard edges of clearcuts. Complex canopies allow some wind penetration, providing consistent, low-level wind exposure that facilitates development of windfirmness throughout the canopy (O'Hara 2014). Additionally, because larger, taller trees are exposed to higher levels of wind stress and are more vulnerable to windthrow than smaller, shorter trees, stands containing multiple cohorts of different tree sizes should experience (1) lower overall mortality during high wind events, and (2) more rapid post-disturbance recovery, than even-aged stands with comparable dominant tree age.

The picture is different for two-aged stands. Dispersed patterns of overstory retention in two-aged stands—for example, stands managed using dispersed irregular shelterwood or variable retention systems—create high wind exposure for retained overstory trees, especially during the first decades after harvest. Over the longer term, retained overstory trees may develop wider root systems due to decreased below-ground competition. The improved stability that these changes in root architecture brings may, however, be offset by post-harvest crown development that increases wind stress. Aggregating retention into large groups during irregular shelterwood and variable retention harvest avoids such concerns over wind exposure of isolated trees at the expense of increased edge effects along aggregate boundaries (as described for clearcuts). These effects can be minimized by treatment design (see below).

Implementation ideas—

We are not aware of guidance on minimizing windthrow risks during silvicultural transformation to multi-aged structures, but the following general recommendations are applicable:

- If available management information indicates above-average windthrow hazard, this should be viewed as an important constraint to management freedom (step 3 in the Transformation Framework, chapter 3) when planning the transformation sequence. If information on windthrow hazard in the target stand does not currently exist, an expectation of potential risk levels can be developed using information on biophysical factors for the site, such as topography and landscape position, soil type and depth, existing species composition and available meteorological data (e.g., prevailing winds, frequency of high wind events) (fig. 9.3). Incorporating observations of windthrow—both in the stand and visible in adjacent stands—into the stand examinations used to describe existing conditions (chapter 4) is a good way of generating data to evaluate windthrow risk.
- Match the target stand structures to the windthrow hazard on the site. Uneven-aged structures and management systems (e.g., single-tree selection) are more suited to topographically exposed sites and sites with soils that inhibit root development than are two-aged stands with dispersed overstory trees.
- Use incremental reductions in overstory density during the transformation sequence to promote windfirmness in residual trees and minimize sudden wind exposure. This applies equally to intermediate treatments and regeneration harvests. For example, if resources allow, consider using a multi-stage irregular shelterwood harvest to progressively achieve the target residual overstory density (see examples in chapter 8).
- The nuances of treatment application can make a difference to windthrow risk.
 - Windloading on trees at gap edges may be reduced by (1) using irregular gap shapes in group selection harvests and variable density thinning, and (2) irregular cut boundaries in aggregated irregular shelterwood and variable retention harvests (i.e., avoiding hard, square canopy boundaries).

- *Edge feathering* at cut boundaries in aggregated irregular shelterwood and variable retention harvests and along the edges of larger gaps in group selection harvests can reduce windloading on edge trees. Edge feathering can take the form of (1) gradual vertical profiling at cutblock edges by retaining understory trees adjacent to the open harvest area to help lift the wind up over the edge, or (2) thinning the edge to allow partial wind penetration into the uncut forest (British Columbia Ministry of Forests 2003). The latter technique is especially effective when the thinning preferentially removes trees that are likely to be less windfirm.
- Select trees for retention based on windfirmness. Although taller trees with larger crowns experience greater wind force, these individuals typically also have lower height-to-diameter ratios and larger, deeper root systems that provide greater stability. Where soil types are conducive to root development, these trees are good candidates for retention. As these trees are typically more vigorous, their retention also furthers other objectives, such as providing quality seed source (British Columbia Ministry of Forests 2003).

The *Silvicultural Systems Manual for British Columbia* (British Columbia Ministry of Forests 2003, based on Mitchell 1998) provides an excellent review of windthrow risk in the context of silvicultural prescription development. If informal analysis or existing documentation indicates that windthrow hazard for a target stand is high, the detailed windthrow assessment contained in this silvicultural text provides a good framework for more detailed evaluation (fig. 9.3). Although this assessment procedure adds complexity to the silvicultural transformation process, it may be worthwhile for stands with high resource value or which occupy prominent, high-visibility locations.



Observed Damage

1. Complete Windthrow Field Card Assessment Pages A and B in a nearby 2–5 year old cutblock on a High Treatment Risk Boundary.
2. Record initial evaluation of windthrow from Assessment Card Page B.

Initial Evaluation (from Assessment Card Page B):

	Very High	High	Moderate	Low	None
Topographic Hazard	•	☐	☐	☐	•
Soil Hazard	•	☐	☐	☐	•
Stand Hazard	•	☐	☐	☐	•
Biophysical Hazard	☐	☐	☐	☐	•
Treatment Risk	•	☐	☐	☐	☐
Windthrow Risk	☐	☐	☐	☐	☐

Calibration of Windthrow Risk Classification

3. Record observed damage on calibration boundary.

Trees Damaged (%):

First Tree Length	☐ >70	☐ 10–70	☐ <10
Second Tree Length	☐ >70	☐ 10–70	☐ <10
Third Tree Length	☐ >70	☐ 10–70	☐ <10
Describe Damage:	☐ Extensive	☐ Partial	☐ Minimal ☐ None

Characteristics of Downed Trees:

Size (compared to mean tree)	☐ Same	☐ Smaller	☐ Larger
Species Composition	☐ Same	☐ Different: (describe) _____	
Rot (compared to average in stand)	☐ Same	☐ Less	☐ More

4. Look up the expected level of damage for your initial Windthrow Risk Class on Reference Page B, and compare with actual damage recorded above.

Diagnostic question: Is the level of damage observed along the calibration boundary consistent with that predicted for the estimated class of Windthrow Risk? (See top of Reference Page B)

If	Action
Yes, damage is consistent with expected level. ☐	Use the values for topographic, soils, and stand indicators to identify threshold values for high, moderate, and low hazard classes for each of the Exposure, Soils, and Stand Hazard components.
No, there is less damage. ☐	Consider which of the component hazards (Exposure, Soils, or Stand) might have been rated too highly. Reduce the rating and raise the hazard class thresholds accordingly.
No, there is more damage. ☐	Consider which of the component hazard (Exposure, Soils, or Stand) might have been rated too low. Increase the rating and decrease the hazard class thresholds accordingly.

5. Use the revised thresholds for classifying Soils, Topographic and Stand Hazards for nearby areas.

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Figure 9.3—Page A of the field card for assessing windthrow risk used by the British Columbia Ministry of Forests, Forest Practices Branch (British Columbia, Ministry of Forests, 2003, based on Mitchell, 1998). Courtesy figure by British Columbia Ministry of Forests, used with permission. Not for re-use without permission of British Columbia Ministry of Forests.

Insects and Pathogens

Insect pests, fungal pathogens, and parasitic organisms are important disturbance agents in ponderosa pine forests (fig. 9.4), especially when acting in concert with other stressors, such as drought and fire. The incidence of some of these biological disturbance agents is affected by stand structure, while in other cases stand structure has little influence on pest or pathogen occurrence and outbreak severity. The discussion below highlights several insects and diseases that are of common management concern in ponderosa pine forests.



Figure 9.4—Bark beetles, such as mountain pine beetle (*Dendroctonus ponderosae*), may have considerable direct and indirect effects on stand structure. In this image from the Black Hills National Forest in South Dakota, mountain pine beetle attack followed by wind disturbance resulted in a major blowdown event and an increase in 1,000-hour surface fuels. USDA Forest Service photo by Mike Battaglia.

Bark beetles—

Outbreak severity of mountain pine beetle (*Dendroctonus ponderosae*) and western pine beetle (*D. brevicomis*), the two most

destructive bark beetles in ponderosa pine-dominated forests, may be influenced by stand structure (e.g., Alexander 1986; Fettig et al. 2007). Low-level (endemic) mortality caused by these two species of bark beetle is widespread in ponderosa pine forests, but high-severity outbreaks are most likely in dense stands (e.g., basal area ≥ 150 ft² per acre) dominated by large (≥ 8 -inch dbh) trees of host species (including ponderosa pine) (Fettig et al. 2022). Large trees are the primary targets of beetles in all but the most severe outbreaks. The consequences of this size preference are magnified in dense stands of mature trees. In such stands, resource constraints often suppress host-tree vigor and this reduces the capacity of trees to produce the defensive compounds required to repel insect attacks.

Stand density index is a primary tool for stand density management in western forests and SDI-based rules have been developed for increasing stand resistance to bark beetles. However, recent research suggests that guidance to limit stand densities to 200–240 SDI (trees per acre with a quadratic mean diameter of 10 inches, e.g., Cochran and Barrett 1995, 1998), may only be effective during periods of relatively low beetle pressure and/or moist climates (Fettig et al. 2022). Under the drier conditions typical of recent decades in western North America, substantially lower stand densities— < 100 to < 150 SDI—may be required to confer high or moderate resistance under severe beetle pressure (Fettig et al. 2022; Hood et al. 2024).

These relationships between stand structure and the risk of beetle-caused mortality provide clues to the likely susceptibility of different multi-aged structures. Important differences exist between even-aged and uneven-aged structures. Even-aged stands pass through a phase in which all stems are smaller than the size threshold for host tree preference, but will then enter a period (an extended period when managing over long rotations) during which most stems will be preferred hosts, based on size. Uneven-aged stands, on the other hand, will typically contain a population of large, preferred host trees throughout the entire cutting cycle. These trees will be particularly vulnerable when a dense understory and midstory creates pressure for resources. However, when stand densities are low and trees remain vigorous, the large trees in uneven-aged stands should be more able to repel beetle attack. At the stand-scale, these uneven-aged structures should also be relatively resilient to beetle attack because younger cohorts are not preferred beetle targets so will typically survive if larger trees succumb (Negrón et al. 2008). Most two-aged structures will exhibit elements of the even-aged temporal shift from less to more exposed, based on tree size, but will possess growing stock in the

lower-risk size category for more time than an even-aged stand with the same overstory age.

Bark beetles in the *Ips* genus (notably the pine engraver, *Ips pini* (Say)) rarely cause major mortality incidents on the scale of those triggered by mountain and western pine beetles. However, they are important drivers of smaller scale and background mortality, as well as reduced productivity (Kegley et al. 1997). Moreover, *Ips* are an especially important consideration for planning forest management activities, as slash and other down woody debris are their primary breeding and overwintering habitat (Six et al. 2002).

In the absence of active management, *Ips* are typically associated with post-disturbance stands, where dying trees, snags, and down woody debris provide abundant feeding and breeding substrate. Slash and larger-diameter fuels generated by logging activities replicate these conditions and provide ideal breeding habitat for the beetles. During favorable conditions, when trees are weakened by environmental stressors, irruptive attacks by large populations of recently hatched adult *Ips* may spread from slash to surrounding live trees, killing and causing top-kill that predisposes trees to other secondary beetles (Kegley et al. 1997). This is especially problematic in young plantations following pre-commercial or early commercial thinning. Trees in these stands may already be stressed by high stand densities, and slash generated by management creates the habitat to support initial *Ips* attacks, which later spread to live trees. This is an especially important consideration for silvicultural transformations in homogeneous young plantations (existing condition Type 1, chapter 4).

Adjusting the timing of thinning and slash management are important tools for minimizing the risk presented by *Ips* during silvicultural transformation. Slash generated during spring and early summer management activities is often perfectly timed to support beetles emerging after overwintering. By contrast, slash created by fall thinning that has time to dry out before and during the winter is poor breeding substrate (Kegley et al. 1997). Slash management practices are equally important. Studies in western Montana suggest that chipping slash to reduce particle sizes and concentrating slash into a small number of locations rather than distributing it evenly throughout the stand may reduce risks from pine engraver (Six et al. 2002). Whole-tree harvesting followed by pile burning tops at landings or removing residues from the site prevents the build-up of the slash that supports *Ips*. However, broadcast burning may increase risks by weakening surviving trees and creating more dead material (Six and Skov 2009).

Fungal pathogens—

Root diseases, including annosus root rot (*Heterobasidion annosum*), black stain root disease (*Leptographium* (syn. *Verticicladiella*) *wagneri*), and *Armillaria* spp. are among the most destructive fungal pathogens in ponderosa pine forests. These diseases are most prevalent (in the case of annosus, exclusively) to the west of the Continental Divide in the northern Rocky Mountains. Except for tree species composition (i.e., availability of hosts), existing research does not suggest any significant relationship between stand structure and fungal pathogen outbreak severity.

As with most stressors, managing stands at lower density to maximize tree vigor may reduce individual tree susceptibility. Minimizing harvest-related injuries to residual trees, another general recommendation for fungal pathogen management, is also applicable. However, annosus root rot, black stain root disease, and *Armillaria* spp. may also be transmitted directly as fungal spores or indirectly via insect vectors from stumps or dead root systems. Therefore, in locations with existing infection sources, it is possible that the more frequent harvesting typical of multi-aged management systems may result in more rapid spread of pathogens than in even-aged systems with similar maximum tree age.

As with even-aged management, the risk of spreading annosus spores can be mitigated by application of borax¹ to cut stumps of harvested green trees. This treatment must be applied within a short (24–72 hours) post-harvest window and is required at any time of year because of year-round spore viability (USDA Forest Service 2017).

Comandra blister rust, caused by the fungus *Cronartium comandrae* (Pk.), is a widespread disease of hard pines throughout the United States, including ponderosa and lodgepole pine in the western U.S. (Johnson 1986). Infection may lead to reductions in productivity, deformity, and mortality. Indeed, comandra is one of the few fungal pathogens that can cause economically important losses in the otherwise relatively disease-resistant ponderosa pine. Damage caused by the rust depends greatly on tree size and the infection site. Young seedlings are often killed within several years of infection, while vigorous overstory trees may survive or live for decades before succumbing. Infections on the bole are most serious, with the fungus slowly girdling the tree (Johnson 1986). Infections on branches may progress to the bole, but the disease

¹ Cellu-treat ® (Nisus Corporation) is commonly used in the Northern Region for liquid application stump treatment.

can also be halted if the branch dies before the infection spreads to the bole.

Pruning to remove infections or selective harvesting of infected trees are potential management options for stands with comandra infections. In even-aged stands, targeted harvesting of infected trees provides an opportunity to create gaps that facilitate regeneration of a new cohort as part of a transformation sequence (see Chapter 8, *Lolo National Forest Case Study*). For this to be effective, removing all infected trees from disease pockets will likely be required. Planting in harvest gaps may also present a lower risk strategy.

Dwarf mistletoe—

Dwarf mistletoes are small parasitic plants that reduce host productivity and may eventually cause mortality (fig. 9.5). While dwarf mistletoe is a lesser management concern in ponderosa pine forests of the northern Rocky Mountains than in the southwestern U.S. or southern Rocky Mountains (Alexander 1986), the range of western dwarf mistletoe (*Arceuthobium campylopodum*) does include northern and central Idaho, and isolated areas of northwestern Montana (Montana Field Guide 2024; USDA NRCS 2024). Where it does occur, dwarf mistletoe infection can cause reductions in tree vigor and productivity, sometimes leading to mortality (Alexander 1986; Hawksworth 1961). Importantly, reductions in vigor and changes in the physical structure of host trees caused by mistletoe infection may interact with other disturbances in ways that may reinforce or counteract the effects of mistletoe infection at tree to landscape scales (Shaw et al. 2022 and references therein). For example, reductions in vigor make trees more vulnerable to insect pests and fungal pathogens. Large witches' brooms that develop in host tree crowns in response to mistletoe infection exemplify potential changes in host-tree physical structure and may alter windthrow risk by increasing localized foliage area and asymmetry of foliage distribution in tree crowns (Shaw and Agne 2017).



Figure 9.5—Bole (left) and branch (upper and lower right) western dwarf mistletoe (*Arceuthobium campylopodum*) infection in young ponderosa pine. Such infections can weaken the host tree, physically and physiologically, and create structural deformities that alter fire hazard and susceptibility to other disturbances. Courtesy image by David Shaw, Oregon State University.

Interactions between dwarf mistletoe and fire are particularly relevant to the management of ponderosa pine forests. Dwarf mistletoe is highly susceptible to fire, both directly through flame, heat, and smoke effects on mistletoe plants, and indirectly through the effect on host tree survival (Alexander and Hawksworth 1976; Shaw and Agne 2017; Wicker and Leaphart 1976). Consequently, the interaction of time-since-last fire and host tree abundance across the landscape may help explain dwarf mistletoe distribution (Alexander and Hawksworth 1976). At the scale of individual trees, structural changes in tree crowns caused by dwarf mistletoe infection alter canopy fuels in ways that should increase fire risk (Shaw and Agne 2017). This includes witches' brooms, which appear to have higher flammability than uninfected areas (Shaw et al. 2022), as well as dead branches and reductions in crown

base height where low-hanging witches' brooms prevent branch shedding.

Studies in ponderosa pine suggest that crown scorch increases with dwarf mistletoe rating (DMR, see below), a metric of mistletoe infection severity, and that mistletoe infection increases the likelihood of post-fire mortality (Conklin and Geils 2008; Harrington and Hawksworth 1990). Findings from efforts to translate these effects on infected trees into changes in stand-scale fire behavior are equivocal and subtle, although this may owe in part to challenges in accurately modeling fire behavior (Shaw and Agne 2017). For example, while dwarf mistletoe infection has not been linked to increased fire spread, fireline intensity, or flame length, surface fire can transition to the canopy with lower windspeeds (Hoffman et al. 2007). Despite these mixed findings, there are reasons to believe that dwarf mistletoe infections may increase overall mortality risks in ponderosa pine stands through interactions with other disturbance agents, including fire.

The mechanism of seed dispersal used by dwarf mistletoe makes some stand structures more vulnerable than others. Seeds are ejected from the crown of infected trees to distances of 52 ft (16 m), although 6–12 ft (2–4 m) is most common (Robinson and Geils 2006). A sticky seed coating allows the seeds to adhere to the surfaces of other vegetation, especially in lower canopy layers. Multi-aged stands with moderately-spaced overstory trees and a midstory and/or understory of seedlings, saplings, and small trees create the perfect conditions for dwarf mistletoe spread from infected trees (O'Hara 2014). Because of the potential vulnerability of stands—multi-aged or even-aged—that contain multiple canopy layers for some or all the cutting cycle/rotation to mistletoe spread, high-severity mistletoe outbreaks are the only situation in which clearcutting has been recommended for managing ponderosa pine in the southern Rocky Mountains (Alexander 1986).

In the Colorado Front Range, where dwarf mistletoe can be a major management constraint, Alexander (1986) recommends evaluating stands that have existing dwarf mistletoe presence using the dwarf mistletoe rating (DMR) system (Hawksworth 1961, 1977). This is a six-class ranking (fig. 9.6) that can be applied to individual trees (fig. 9.7) or stands. Recommendations were to limit multi-aged harvest methods to stands with an average DMR rating of three or less. Such guidance should be used during the early stages of planning whether and how silvicultural transformation might be applied in a given target stand.

Instructions for tree evaluation:

Step 1. Divide live crown into thirds.

Step 2. Rate each third separately. Each third should be given a rating of 0, 1, or 2 as described below.

(0) - No visible infections.

(1) - Light infection ($\leq$ half of total number of live branches in the third infected).

(2) - Heavy infection ($>$ half of total number of live branches in the third infected).

Step 3. Finally add the ratings of the thirds to obtain the rating of the total tree.

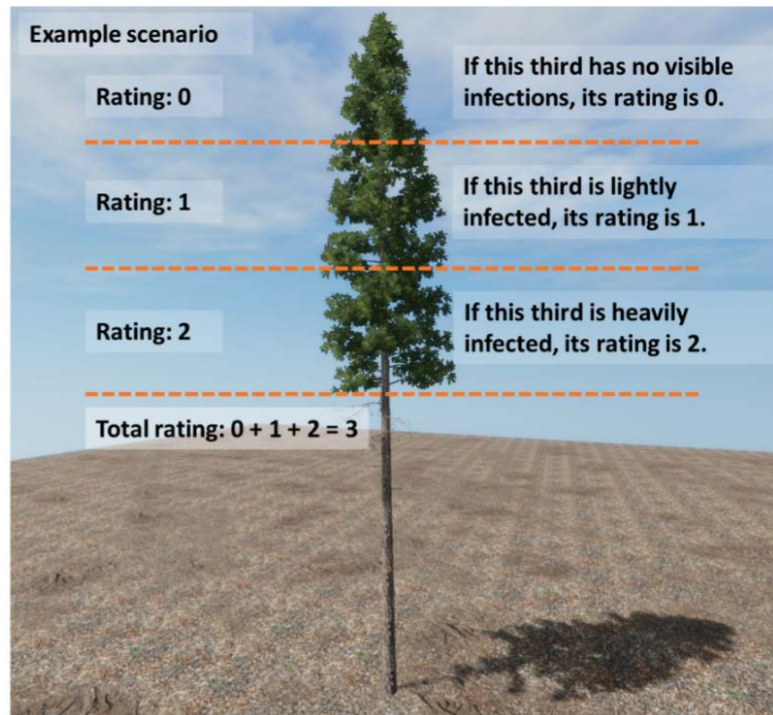


Figure 9.6—The six-class mistletoe rating system of Hawksworth (1961) involves assigning a rating to each third of the live crown. The rating system provides a simple way to characterize the degree of infection in trees and stands.



Figure 9.7—(Left) The tree in the center of this image is heavily infected with dwarf mistletoe throughout the crown, producing a heavily clumped distribution of foliage. This tree should be assigned a DMR value of 6 ($2 + 2 + 2$). (Right) The tree in the center of this image shows heavy dwarf mistletoe infection in the lower crown, producing witches' brooms and unequal foliage distribution around the bole, while the middle third of the crown shows some signs of infection and the upper crown is mistletoe-free. This tree would be assigned a DMR value of 3 ($2 + 1 + 0$). Courtesy image by David Shaw, Oregon State University.

Even with tools such as the DMR system, the wisdom of attempting a silvicultural transformation in stands with an existing dwarf mistletoe infection should be assessed on a stand-by-stand basis. Factors such as the stem density and spatial configuration of infected trees are important considerations. Stands with widely dispersed infected trees present more of a problem than those where existing infection centers are clumped and potentially removable by careful, targeted sanitation cutting. Sanitation harvests have been used in stands with low to moderate dwarf mistletoe incidence (Alexander 1986).

Prescribed fire is another promising means of controlling intermediate mistletoe incidence (Shaw and Agne 2017). Used in isolation, prescribed fire can help arrest mistletoe spread by killing mistletoe, suppressing mistletoe seed production, and killing host trees (Conklin and Geils 2008; Irving and French 1971; Shaw and Agne 2017). The effectiveness of prescribed fire is likely to increase when used in combination with sanitation or improvement cutting (Hessburg et al. 2008), the latter of which may be used to selectively remove pine in localized infection centers. However, the desirability of reducing or removing mistletoe infection is likely to depend as much on management objectives as biophysical factors.

As with the treatment of snags and logs when managing fire hazard, tensions exist between managing for wildlife habitat value and future disturbance risks in stands with a dwarf mistletoe infection. Trees with dwarf mistletoe infections may have high habitat value for many wildlife species. This is because infections often cause trees to develop complex branch formations and crown architecture, including witches' brooms, and may eventually lead to partial mortality (trees with both live and dead limbs). For this reason, infected trees may be retained on ecological grounds.

Retention of too many infected trees, however, increases the risk of failing to regenerate and nurture new ponderosa pine cohorts during the transformation to a multi-aged structure. Opting to transform stands with an existing dwarf mistletoe presence, therefore, requires site-specific evaluation of existing stand structures and management objectives. If this evaluation suggests that silvicultural transformation is appropriate and possible, the continued presence or absence of dwarf mistletoe may be included in the description of a desired future condition. In such circumstances, deliberate steps will be required to ensure continuity of mistletoe-infected trees without risk of widespread mistletoe dispersal.

Marking in Multi-Aged Management

Background—

There is a perception that marking for regeneration harvests in multi-aged silvicultural systems is complex, time-consuming, and require a higher level of skill and experience than marking in most even-aged systems (e.g., Powell 2018). This perception may act as a deterrent to implementing multi-aged practices. Some regeneration harvest methods and stocking control practices may indeed involve complex marking guides. However, in practice, the degree of complexity and resources involved in marking for multi-aged regeneration harvests varies widely according to the type of harvest and the stocking control methods that are employed.

Single-tree selection harvests with BDq-based stocking control, and an irregular shelterwood harvest provide very different examples of marking in multi-aged stands. The BDq method of stocking control is often thought to be particularly burdensome because of the demands involved in conforming to the target distribution. Aligning the stand with the distribution requires a relatively high level of skill and is likely to be time-consuming and resource-intensive. Such demands have even deterred widespread implementation of strict BDq-based marking in the eastern United States, where uneven-aged management is more common than in ponderosa pine forests. Harvests may be relatively demanding in terms of time, resources, and the level of skill required. By contrast, marking an irregular shelterwood harvest in ponderosa pine stands may involve relatively simple marking that is little different from that of a conventional even-aged shelterwood, depending on the prescription. The longer period over which residual overstory trees are retained in an irregular shelterwood than in a conventional shelterwood may warrant additional emphasis on future growth potential and windfirmness. However, in many cases, marking decisions to meet these objectives will result in the retention of trees similar to those that would have been chosen based on potential for seed supply and shelter in a conventional shelterwood harvest. These desirable physical characteristics and the intended spatial pattern of retained trees in the irregular shelterwood can easily be conveyed to marking crews. Thus, a spectrum of marking complexity exists across the various regeneration harvest methods and forms of stocking control.

In figure 9.8 we depict this spectrum using two axes. These axes represent complexity arising from (1) the use of detailed quantitative targets, and (2) the specification of residual tree, tree neighborhood, or stand-scale attributes that are based on ecological objectives. The latter ecological objectives often require a high level of ecological knowledge to optimize and may be difficult to define

The degree of complexity and resources involved in marking for multi-aged regeneration harvests varies widely according to the type of harvest and the stocking control methods being employed.

quantitatively or operationalize from qualitative descriptions. As this spectrum implies, it is possible to design multi-aged systems that do not impose a high burden on marking crews, as well as systems that will entail more skill, experience, and/or time to implement. The placement of harvest types and stocking control methods shown in figure 9.8 is undoubtedly “fuzzy” and masks considerable within-treatment variation. Instead, our positioning of the practice labels on these axes of marking complexity highlights broad generalities that might be expected for the implementation of these practices in ponderosa pine stands.

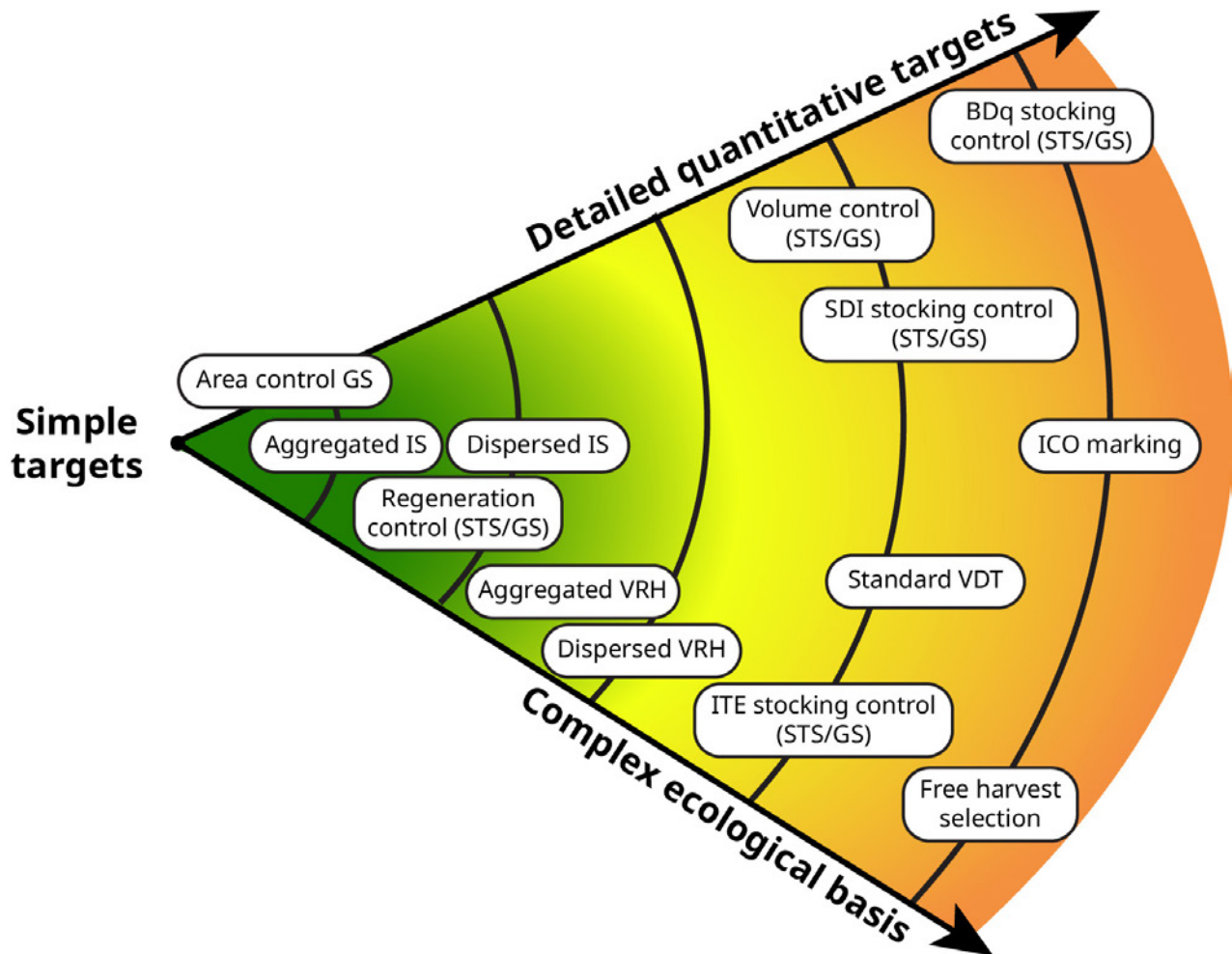


Figure 9.8—A conceptual representation of the dimensions of complexity associated with marking harvests in a multi-aged management system. In this representation, complexity can stem from quantitative targets and ecological knowledge required to implement the marking guide. As the off-perpendicular angle of the axes implies, there is often a correlation between methods that utilize more detailed quantitative targets and those that require more ecological background in order to realize their full potential. Acronyms: GS – group selection, IS – irregular shelterwood, STS – single-tree selection, VRH – variable retention harvest – ITE – individual tree evaluation, Standard VDT – the common current approach to variable density thinning involving skips, gaps and matrix, ICO – individuals, clumps and openings (method of marking stands).

Below, we provide brief examples of practices located at the edges of the two marking complexity axes.

- The BDq method of stocking control in single-tree or group selection harvests is an example of a method that involves complexity stemming from the use of detailed quantitative targets. These targets are the numerical guides for stem numbers in each diameter class of the chosen reverse-J diameter distribution. ICO marking is another approach that involves the use of relatively detailed quantitative targets. This time, the targets are in terms of the number of trees in clumps of different sizes. In figure 9.8, we position ICO between the two complexity axes because, to a greater extent than the BDq approach, experience with ICO marking suggests that this approach benefits from a sound understanding of the ecological rationale behind the practice and individual marking decisions (e.g., Maher et al. 2019).
- Free selection avoids the detailed numerical targets of the BDq or ICO systems in favor of flexibility and expansive qualitative structural goals. In theory, such methods have the advantage of liberating marking crews from detailed measurement against extensive numerical targets. A disadvantage of this flexibility and lack of numerical guides is that marking crews take on considerable responsibility for creating structures that achieve the desired ecological outcomes of this ecologically-based silvicultural system . A comparison between marking in free selection harvests and comparable ICO-based harvests suggested that ICO's quantitative sideboards and the ability to translate these targets into real-time, tablet-based monitoring of marking progress may improve marking speed and the ability to achieve desired structural outcomes (Maher et al. 2019).

Training also improves marking outcomes. Managers can include training opportunities when selecting and developing crews for annual or multi-year marking campaigns that will involve significant amounts of work with complex multi-aged harvest methods or stocking control practices during or after silvicultural transformation. Indeed, widespread implementation of transformation silviculture in northern Rocky Mountain ponderosa pine stands would greatly benefit from developing a regional pool of marking crews skilled in the theory and practice of multi-aged harvest practices.

In summary, there is considerable variability in the potential complexity of marking multi-aged regeneration harvests depending

on the type of harvest, the method of stocking control, and according to the nuances of individual stands and management objectives. Generally, marking multi-aged regeneration harvests will require more time and/or crews that are more experienced and comfortable with detailed quantitative targets or ecological concepts than will even-aged regeneration harvest methods. However, it is possible to design marking approaches for multi-aged harvests that are relatively straightforward.

Implementation ideas—

To an extent, the process of marking a harvest is specific to the site, the stand, the specifications of the harvest, and the preferences of the individuals conducting the marking. However, the silvicultural literature does offer some pointers and tips on multi-aged marking that may be useful when adopting unfamiliar multi-aged harvest practices, especially when they involve relatively complex marking guides. Some of the ideas listed below are generalizable across harvest types, while others are suited to specific harvest methods, forests, or site conditions. We focus on guidance that is relevant to ponderosa pine forests. As with other aspects of implementing transformation to multi-aged structures, we also strongly advise contacting any local practitioners or extension foresters familiar with regional application of multi-aged methods. Talking to foresters with hands-on experience can be the most effective way of gaining practical tips.

- Leave-tree marking is widely recommended. Although some practitioners recommend selecting between leave-tree or cut-tree marking based on whichever is quickest and least-costly in a given situation (Powell 2018), there is a preference for leave-tree marking in literature derived from applied research, including in ponderosa pine forests (e.g., Fiedler 1999; Fiedler et al. 2007). Leave-tree marking helps visualize post-harvest residual structure. This is particularly advantageous in management applications designed to generate specific spatial patterns and/or retain specific structural elements. Marking leave trees helps ensure that the residual structure is positively selected based on desirable tree or stand attributes, rather than being the sum of material that wasn't harvested (Fiedler 1995; Mitchell et al. 2006).
- In general, mark to leave the most vigorous trees and cut the less vigorous (Guldin and Baker 1998) but ensure that some of the less vigorous trees are also retained. Vigorous trees are typically a desirable seed source, ensure good productivity following harvest, and are often the most

windfirm. However, retaining a population of less vigorous trees during harvest ensures continuity of the ecological functions (e.g., wildlife habitat) that trees provide during the senescence process and after death as snags and logs (Palik et al. 2020). To the extent that it is compatible with fire hazard management objectives, marking guides should also explicitly include provisions for the retention or creation of some snags. Ideally, existing snags should be retained across decay classes. This is because (1) snags in different stages of the decay process provide resources for different species of wildlife, and (2) including a range of decay classes, including freshly created and soon-to-be snags, creates a pipeline of snags that will progress through the decay stages over time after harvest (Barry et al. 2017, 2018).

- Marking crews should periodically evaluate progress toward residual structural targets. This can be achieved through brief sample check-tallies, swinging a basal area prism, or other favored methods (Powell 2018).
- In selection systems (single-tree, group, or free), developing separate marking guides is strongly recommended in situations where intermediate treatments, such as thinning or improvement cutting, are to be accomplished at the same time as regeneration harvests. In these circumstances, each treatment should be marked separately, ideally by different personnel (Powell 2018).
- When developing a marking guide for use with the BDq method for single-tree or group selection, express marking targets in 4- to 6-inch diameter classes. Two-inch diameter classes are typically recommended for monitoring the diameter distribution and identifying cut targets, but these 2-inch classes can be aggregated for marking guides (Guldin and Baker 1998; Powell 2018).
- Using primarily aggregated retention rather than dispersed retention in irregular shelterwood and variable retention harvests should reduce time and simplify marking for crews. Patch sizes in aggregated retention are often large enough to constitute major harvest planning decisions that should be determined by the forester/silviculturist, which shifts the responsibility for delineating aggregate locations away from marking crews.
- Implementing marking for complex treatments with qualitative structural targets or detailed quantitative targets

such as free selection, restoration treatments, and variable density thinning benefits greatly from training the marking crews on the ecological rationale and objectives before their first marking sessions. Providing debriefs and post-treatment analysis of outcomes against targets may also be helpful during the initial uptake of these methods. This investment can yield performance and efficiency benefits, but is most valuable when marking crews can be retained or re-engaged across marking seasons to work on many stands receiving similar multi-aged treatments.

- For gap-based harvests that involve restoration-based ecological objectives, explicit specification of desired gap sizes in the marking guide is advisable for gaps at the upper end of the desired size range. Marking guides for restoration treatments, in particular, often implicitly assume that openings of the desired sizes will emerge as a product of designating residual trees and clumps. Some studies, however, suggest that this is generally not the case for the largest gap sizes (e.g., Churchill et al. 2013, 2017). The absence of larger gaps fails to replicate pre-settlement structure and may also hinder ponderosa pine regeneration and bias regeneration conditions toward the requirements of more shade-tolerant species.
- Encourage marking crews to vary the marked specification (whether this is leave-tree spatial pattern, clump sizes, basal area, or any other metric) across the stand. Shifting stands toward a structure that more closely approximates the assumed pre-Euro-American settlement structure is a common objective of many silvicultural transformations in ponderosa pine forests. Even where ecological restoration is not a primary treatment objective, increasing within-stand structural heterogeneity is more consistent with the natural model of stand development. Thus, it should better mimic the processes and functions associated with sustainable ponderosa pine stand structures (e.g., habitat provision), including resilience to disturbances.
- Marking guides that provide quantitative structural targets may inadvertently promote uniformity of spatial patterns at scales beyond the tree neighborhood, but relatively simple options for counteracting this tendency exist. As one example, instruct marking crews to divide the stand into approximate quadrants. Then, adjust one or more target marking statistics (e.g., by a set percentage) from one

quadrant to the next, while maintaining an approximate average equal to the stand-scale target listed in the marking guide. For instance, if the marking guide includes a target residual tree density in the 10–20-inch diameter class of 30 trees per acre, marking crews could apply this as targets of 22, 28, 32, and 38 trees per acre in each quadrant of the stand. Implementing this process need not be terribly precise to realize the benefits in terms of increased heterogeneity.

- Encourage discussion within marking crews during and after marking to facilitate shared learning and improvement (Graham et al. 2006). Feedback between marking crews and foresters/silviculturists should be a two-way process to foster continual improvement of all elements of the treatment design and implementation process.

Summary

Transformation from even-aged to managed multi-aged structures in northern Rocky Mountain ponderosa pine forests may help align stand structure with many common forest management objectives. Transformation is a flexible process in which the end point—the desired future condition—can be tailored to suit site characteristics, management objectives, and constraints. Differences in the number of cohorts (two-aged or uneven-aged), the spatial distribution of each cohort (aggregated, clumped, dispersed, or a combination), and the amount of growing space allocated to each cohort create an array of possible future conditions. In all cases, these multi-aged stands will provide continuous tree cover, which has many benefits, including aesthetic and recreational values, and continuity of important regulatory functions such as hydrological regulation, soil stabilization, on-site carbon storage, and tree seed production. Ponderosa pine-dominated forests in the northern Rocky Mountains were largely uneven-aged before Euro-American settlement of the region. Thus, transformation will typically also improve consistency with the structure and ecological function of forests developing under the natural model (supplemented in some areas by Indigenous burning). Therefore, while transformation to multi-aged structures will certainly not be suitable in all circumstances, there are many reasons to consider its potential applicability.

In this guide, we proposed a stepwise transformation framework that involves data collection and planning in addition to the silvicultural treatments that accomplish the transformation, which we term the transformation sequence. Describing existing conditions is necessary for developing effective treatments to begin the transformation and provides an important “sense-check” when developing a realistic desired future condition. Reviewing management objectives—including the timeframe over which these objectives must be achieved—and site-specific management constraints helps in developing the desired future condition. This may also influence the choice and timing of treatments in the transformation sequence. The range of desired future conditions should be described to a level of detail and in formats that are most useful for those involved in implementing the transformation process. This description of desired future conditions will act as a blueprint for foresters for many decades to come. The future condition should ideally incorporate concepts of spatial and temporal variability. Developing a plan for the transformation sequence that shifts the stand from existing to desired future conditions provides clarity over the direction of travel for those implementing the transformation, now and into the future. Equally important is management flexibility and a willingness to

deviate from plans when unexpected stand development induces a departure from the planned direction of travel.

The range of silvicultural treatments that may have a place in the transformation sequence, and in subsequent multi-aged management, is broad and encompasses regeneration harvests and intermediate treatments. Treatment options include classical silvicultural methods as well as more recently popularized approaches. These treatments vary in effect, intent, and the degree of complexity associated with treatment design, marking, and implementation. While regeneration harvests are a natural focus of the transformation to multi-aged structure, intermediate treatments will typically be just as consequential to transformation success. The wide array of treatment options, combinations, and timing create the potential for an almost limitless number of different transformation sequences. This makes it possible to design transformation sequences that are tailored to the differing site and stand conditions and management objectives and constraints that exist within ponderosa pine's broad range.

In this guide we highlighted examples of ongoing transformation to multi-aged structure in ponderosa pine forests of the northern Rocky Mountains. These examples are from a small number of accessible sites in western Montana, but transformation to multi-aged structure is ongoing at other sites in the Inland Northwest. Each of these examples yields lessons for managing transformation to multi-aged structures in ponderosa pine stands. Among these lessons are the importance of:

- site preparation and understory vegetation management (both of which may involve prescribed burns and/or mechanical treatments) in creating favorable seedbed conditions and controlling shade-tolerant understory conifers,
- preferentially harvesting a high proportion of pre-existing overstory Douglas-fir and grand fir, especially when these species are widely dispersed throughout the stand, to restrict establishment of ponderosa pine's more shade-tolerant competitors, and
- allowing more time for natural seedling establishment, where regulations permit, than the typical five-year, post-harvest stocking period, or using low reforestation stocking densities that account for residual overstory seed sources.

Visiting the example sites featured in this guide and others elsewhere will provide valuable learning opportunities for planning transformations.

Accounting for management objectives when developing the transformation sequence enables the design of treatments that ensure stands will continue to meet resource demands during the transformation process. Minimizing disturbance hazard is a common management objective in the northern Rocky Mountains. Understanding the contribution of individual structural elements and their spatial arrangement to disturbance hazard is central to designing a transformation sequence that minimizes disturbance hazard. Although some multi-aged stand structures may increase certain components of disturbance hazard, compared to even-aged structures, transformation to multi-aged structure can reduce other components of disturbance hazard. As with even-aged silviculture, matching stand structures—during and after the transformation—and silvicultural treatments to site conditions, local landscape context, and management constraints is key to adjusting to and mitigating disturbance risks in multi-aged stands.

This guide and other sources provided in the reference list can assist with the transformation from even-aged (and related structures resulting from shade-tolerant infilling) to multi-aged structures in ponderosa pine stands. Combining this information with knowledge of site and species silvics, and of the diverse silvicultural toolkit, provides the practical and technical resources to manage transformation and implement multi-aged management in ponderosa pine stands.

Annotated Reference List

References cited in this management guide are listed below. Resources that we feel have some special value for implementing transformation to and management of multi-aged ponderosa pine stands are highlighted using •• symbology.

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Washington DC: Island Press. 505 p.

Agee, J.K. 1996. The influence of forest structure on fire behavior. Proceedings of the 17th Annual Forest Vegetation Management Conference; Jan. 16–18; Redding, CA: University of California, Agriculture and Natural Resources: 52–68.

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••Alexander, R.R. 1986. Silvicultural systems and cutting methods for ponderosa pine forests in the Front Range of the central Rocky Mountains. Gen. Tech. Rep. RM-GTR-128. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 22 p. <https://doi.org/10.2737/RM-GTR-128>

Value: Describes the application of selection-based methods for managing uneven-aged ponderosa pine stands in the Colorado Front Range, including detailed quantitative targets for the BDq method of stocking control. Note that this publication treats the BDq system as the only stocking control method for uneven-aged stands, and assumes that a balanced, regulated stand is the goal.

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Arno, S.F. 1980. Forest fire history in the northern Rockies. Journal of Forestry. 78(8): 460–465. <https://doi.org/10.1093/jof/78.8.460>

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••Arno, S.F. 1999. Ecosystem-based management treatments. In: Smith, H.Y.; Arno, S.F., (eds.). Eighty-eight years of change in a managed ponderosa pine forest. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Gen. Tech. Rep. RMRS-GTR-23. p. 22–26.

Value: This chapter from a Forest Service general technical report presents an excellent summary of the rationale behind the irregular shelterwood and selection studies at Lick Creek Demonstration-Research Forest, the management objectives for the stands, and treatment design and the short-term (~ 5-years post-harvest) results of treatment. The following chapter of this report, titled *Effects of Ecosystem-Based Management Treatments* (multiple authors) also contains information on short-term post-treatment responses that may be useful in forming expectations for treatments implemented in stands with similar existing conditions to those here.

••Arno, S.F.; Scott, J.H.; Hartwell, M.G. 1995. Age-class structure of old growth ponderosa pine/Douglas-fir stands and its relationship to fire history. Res. Pap. INT-RP-481. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 25 p.

••Arno, S.F.; Smith, H.Y.; Krebs, M.A. 1997. Old growth ponderosa pine and western larch stand structures: Influence of pre-1900 fires and fire exclusion. Research Paper INT-RP-495. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 20 p.

Value: These two Forest Service general technical reports provide reconstructions of the structure of ponderosa pine and western larch-dominated stands (before Euro-American settlement) in the northern Rocky Mountains for use in developing target stand and age class structures. Useful information in these reports includes quantitative stand summary data, planimetric stem maps of spatial structure, and cohort origination dates. The 1995 publication provides more detailed quantitative information for a larger number of stands, while the 1997 publication adds additional sites with a larger western larch component, and provides a more complete discussion of relationships between stand structure, fire regimes, and site characteristics.

Ashton, M.S.; Kelty, M.J. 2018. The practice of silviculture: Applied forest ecology. Tenth edition. Hoboken, NJ: John Wiley & Sons. 758 p.

Barber, J.; Bush, R.; Berglund, D. 2011. The Region 1 existing vegetation classification system and its relationship to Region 1 inventory data and map products. Numbered Report 11-10. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region. 39 p. https://www.fs.usda.gov/sites/nfs/files/legacy-media/r01/r1_ex_veg.pdf [Accessed 29 May 2025]

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Battaglia, M.A.; Rocca, M.E.; Rhoades, C.C.; et al. 2010. Surface fuel loadings within mulching treatments in Colorado coniferous forests. *Forest Ecology and Management*. 260: 1557–1566. <https://doi.org/10.1016/j.foreco.2010.08.004>

Beese, W.J.; Deal, J.; Dunsworth, B.G. [et al.]. 2019. Two decades of variable retention in British Columbia: A review of its implementation and effectiveness for biodiversity conservation. *Ecological Processes*. 8(1): 1–22. <https://doi.org/10.1186/s13717-019-0181-9>

Berkey, J.K.; Belote, R.T.; Maher, C.T.; [et al.]. 2021. Structural diversity and development in active fire regime mixed-conifer forests. *Forest Ecology and Management*. 479: p.118548. <https://doi.org/10.1016/j.foreco.2020.118548>

Bernal, A.A.; Stephens, S.L.; Callaham, M.A.; [et al.]. 2025. The national Fire and Fire Surrogates Study: Effects of fuel treatments in the western and eastern United States after 20 years. *Ecological Applications* 35:e70003. <https://doi.org/10.1002/eap.70003>

Bradford, J.B.; D'Amato, A.W. 2012. Recognizing trade-offs in multi-objective land management. *Frontiers in Ecology and the Environment*. 10(4): 210–216. <https://doi.org/10.1890/110031>

••British Columbia Ministry of Forests. 2003. Silvicultural systems handbook for British Columbia. Forest Practices Branch, B.C. Ministry of Forests, Victoria, BC. <https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/stand-tending/silvsystemshdbk-web.pdf> [Accessed 29 May 2025]

Value: As well as an excellent practical silviculture guide, this handbook is especially useful for its detailed stepwise procedure for evaluating windthrow risk, accompanied by tips for minimizing windthrow during treatment design.

Callaham, R.Z. 2013. *Pinus Ponderosa*: A taxonomic review with five subspecies in the United States. Res. Pap. PSW-RP-264. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 52 p. <https://doi.org/10.2737/PSW-RP-264>

••Churchill, D.J. 2021. Architecture for archetype 2 ecosystems: Forest characterized by frequent low-severity fire disturbance. In: Palik, B.J.; D'Amato, A.W.; Franklin, J.F.; [et al.]. *Ecological silviculture: Foundations and applications*. Long Grove, IL: Waveland Press.

Value: See also Larson and Churchill, 2023. These excellent accounts discuss the structure and developmental processes of forests with a historic frequent to moderately frequent fire regime. The authors then use the ecological silviculture framework to develop treatment options for producing resilient stand structures associated with forests with an intact disturbance regime. In this, they apply a similar condition-based approach that is used here in RMRS-GTR-446.

••Churchill, D.J.; Larson, A.J.; Dahlgreen, M.C. [et al.]. 2013. Restoring forest resilience: from reference spatial patterns to silvicultural prescriptions and monitoring. *Forest Ecology and Management*. 291: 442–457. <http://dx.doi.org/10.1016/j.foreco.2012.11.007>

Value: This research article provides quantitative reference conditions and targets for ICO application in dry mixed-conifer forests for restoration-oriented treatments. The publication is written as a research communication, but has much applied value. This includes lessons from initial application of ICO-marked treatments and ideas for accommodating climate change considerations into treatment design.

••Churchill, D.J., Larson, A.J.; Jeronimo, S.M.W.; [et al.]. 2016. The ICO approach to quantifying and restoring forest spatial pattern: Implementation guide. Version 3.0. Vashon, WA: Stewardship Forestry and Science. 68 p.

Value: This management-oriented technical note contains the most detailed, practical guidance for implementing ICO-marked treatments that we are aware of, including use of reference conditions to generate spatial patterns, field application of ICO marking using the tablet-based app, and recommendations for determining when ICO might be a suitable approach. The document is written from the perspective of using ICO in restoration treatments, but this is not to the exclusion of wider use of ICO as part of a silvicultural system.

••Churchill, D.J.; Carnwath, G.C.; Larson, A.J.; [et al.]. 2017. Historical forest structure, composition, and spatial pattern in dry conifer forests of the western Blue Mountains, Oregon. Gen. Tech. Rep. PNW-GTR-956. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 93 p.
<https://doi.org/10.2737/PNW-GTR-956>

Value: This technical guide provides reference spatial patterns for dry mixed-conifer stands across a gradient of soil moisture conditions. Later chapters of the guide contain some extremely useful practical ideas for translating reference conditions into restoration treatments. Although developed from stands in the Blue Mountains of Oregon, the reference conditions in this guide are likely to be applicable to a range of sites in the northern Rocky Mountains.

Churchill, D.J.; Jeronimo, S.M.; Hessburg, P.F.; [et al.]. 2022. Post-fire landscape evaluations in eastern Washington, USA: Assessing the work of contemporary wildfires. *Forest Ecology and Management*. 504: 119796.
<https://doi.org/10.1016/j.foreco.2021.119796>

••Clyatt, K.A., Crotteau, J.S.; Schaedel, M.S.; [et al.]. 2016. Historical spatial patterns and contemporary tree mortality in dry mixed-conifer forests. *Forest Ecology and Management*. 361: 23–37. <https://doi.org/10.1016/j.foreco.2015.10.049>

Value: This research article provides quantitative reference spatial patterns for dry mixed-conifer stands in the which ponderosa pine is an important component, located in western Montana. Although this is a written as a research article, it has strong applied value for both the quantitative reference conditions and a strong discussion of the relationship between reference spatial patterns and site characteristics that draws on reference conditions from dry mixed-conifer sites across the western U.S.

••Cochran, P.H. 1992. Stocking levels and underlying assumptions for uneven-aged ponderosa pine stands. Research Note PNW-RN-509. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 12 p.
<https://doi.org/10.2737/PNW-RN-509>

Value: This technical report discusses stocking control concepts in ponderosa pine stands, and is particularly useful for the worked example of SDI allocation stocking control in uneven-aged ponderosa pine stands in eastern Oregon. The document also does a good job of relating stocking levels in uneven-aged stands to those in even-aged stands.

Cochran, P.H.; Barrett, J.W. 1995. Growth and mortality of ponderosa pine poles thinned to various densities in the Blue Mountains of Oregon. Research Paper PNW-RP-483. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 27 p. <https://doi.org/10.2737/PNW-RP-483>

Cochran, P.H.; Barrett, J.W. 1998. Thirty-five-year growth of thinned and unthinned ponderosa pine in the Methow Valley of northern Washington. Research Paper PNW-RP-502. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 24 p. <https://doi.org/10.2737/PNW-RP-502>

Conklin, D.A.; Geils, B.W. 2008. Survival and sanitation of dwarf mistletoe-infected ponderosa pine following prescribed underburning. *Western Journal of Applied Forestry*. 23(4): 216–222. <https://doi.org/10.1093/wjaf/23.4.216>

Creeden, E.P.; Hicke, J.A.; Buotte, P.C. 2014. Climate, weather, and recent mountain pine beetle outbreaks in the western United States. *Forest Ecology and Management*. 312: 239–251. <https://doi.org/10.1016/j.foreco.2013.09.051>

Crotteau, J.S.; Keyes, C.R. 2020. Restoration treatments improve overstory tree resistance attributes and growth in a ponderosa pine/Douglas-fir forest. *Forests*. 11(5): 574. <https://doi.org/10.3390/f11050574>

Crotteau, J.S.; Hood, S.M.; Lutes, D.C.; [et al.]. 2018. Management and succession at the Lick Creek Demonstration/Research Forest, Montana. *Journal of Forestry*. 116(5): 481–486. <https://doi.org/10.1093/jofore/fvy030>

Curtis, R.O. 1998. "Selective cutting" in Douglas-fir: History revisited. *Journal of Forestry*. 96(7): 40–46. <https://doi.org/10.1093/jof/96.7.40>

Dante-Wood, S.K. 2018. Biogeographic, cultural, and historical setting of the northern Rocky Mountains. In: Halofsky, J.E.; Peterson, D.L.; Dante-Wood, S.K.; [et al.], eds. *Climate change vulnerability and adaptation in the Northern Rocky Mountains Part 1*. Gen. Tech. Rep. RMRS-GTR-374. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. <https://doi.org/10.2737/RMRS-GTR-374PART1>

De Liocourt, F. 1898. De l'Amenagement des sapinieres. *Bulletin Trimestriel, Societe Forestie re de Franche-Comte et Belfort*, Juillet 1898: 396–409.

Deal, R. 2018. *Society of American Foresters dictionary of forestry*. Washington, DC: Society of American Foresters. 208 p.

Dixon, Gary E. comp. 2002. (Revised August 2022). Essential FVS: A user's guide to the Forest Vegetation Simulator. Internal Report. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center.

Edburg, S.L.; Hicke, J.A.; Brooks, P.D.; [et al.]. 2012. Cascading impacts of bark beetle-caused tree mortality on coupled biogeophysical and biogeochemical processes. *Frontiers in Ecology and the Environment*. 10(8): 416–424. <https://doi.org/10.1890/110173>

Fajardo, A.; Goodburn, J.M.; Graham, J. 2006. Spatial patterns of regeneration in managed uneven-aged ponderosa pine/Douglas-fir forests of western Montana, USA. *Forest Ecology and Management*. 223(1-3): 255–266. <https://doi.org/10.1016/j.foreco.2005.11.022>

Fajardo, A.; Graham, J.M.; Goodburn, J.M.; [et al.]. 2007. Ten-year responses of ponderosa pine growth, vigor, and recruitment to restoration treatments in the Bitterroot Mountains, Montana, USA. *Forest Ecology and Management*. 243(1): 50–60. <https://doi.org/10.1016/j.foreco.2007.02.006>

Fettig, C.J.; Klepzig, K.D.; Billings, R.F.; [et al.]. 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. *Forest Ecology and Management*. 238(1–3): 24–53. <https://doi.org/10.1016/j.foreco.2006.10.011>

Fettig, C.J. 2012. Forest health and bark beetles. In: North, M., ed. *Managing Sierra Nevada forests*. Gen. Tech. Rep. PSW-GTR-237. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 184 p. <https://doi.org/10.2737/PSW-GTR-237>

Fettig, C.J.; Reid, M.L.; Bentz, B.J.; [et al.]. 2013. Changing climates, changing forests: A western North American perspective. *Journal of Forestry*. 111(3): 214–228. <https://doi.org/10.5849/jof.12-085>

Fettig, C.J.; Egan, J.M.; Delb, H.; [et al.]. 2022. Chapter 11—Management tactics to reduce bark beetle impacts in North America and Europe under altered forest and climatic conditions. In: Gandhi, K.J.K.; Hofstetter, R.W., eds. *Bark beetle management, ecology, and climate change*. Academic Press. 345–394. <https://doi.org/10.1016/B978-0-12-822145-7.00006-4>

•Fiedler, C.E. 1996. Silvicultural applications: Restoring ecological structure and process in ponderosa pine forests. In: Hardy, C.C.; Arno, S.F., eds. *The use of fire in forest restoration*. Gen. Tech. Rep. INT-GTR-341. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 39–40. <https://research.fs.usda.gov/treearch/28487> [Accessed 29 May 2025.]

Value: This two-page article is useful for providing a short, readable overview of possible transformation sequences for developing resilient multi-aged structures from two distinct existing condition types in ponderosa pine stands: overstocked second-growth stands, and overstocked old-growth stands. The transformation sequences are limited in detail and focus on the initial steps in the process, but are nevertheless valuable insights from perhaps the most experienced applied researcher to have worked on this topic in western Montana.

•Fiedler, C.E.; Cully, J.E. 1995. Technical commentary: A silvicultural approach to develop Mexican spotted owl habitat in Southwest forests. *Western Journal of Applied Forestry*. 10(4): 144–148. <https://doi.org/10.1093/wjaf/10.4.144>

Value: This article describes work in ponderosa pine forests in the U.S. Southwest, rather than the northern Rocky Mountains, but has value in providing a thorough worked example of SDI allocation stocking control in a selection-based harvest prescription. The overall research goal is developing wildlife habitat, but much of the information has transferable value to other management contexts. The authors describe some of the advantages of the SDI allocation compared to BDq in uneven-aged silviculture.

Fiedler, C.E.; Arno, S.F. 2015. *Ponderosa: People, fire, and the West's most iconic tree*. Missoula, MT: Mountain Press. 463 p.

•Fiedler, C.E.; Keegan, C.E. III; Wichman, D.P.; [et al.]. 1999. Product and economic implications of ecological restoration. *Forest Products Journal*. 49(2): 19. <https://www.proquest.com/scholarly-journals/product-economic-implications-ecological/docview/214624470/se-2?accountid=28147> [Accessed 29 May 2025]

Value: As with Fiedler, 1996 (above), is research article includes a short, accessible summary of silvicultural prescriptions for restoring resilient multi-aged structures in ponderosa pine stands with different existing conditions. The content is high-level, and not focused on practical implementation, but is useful nevertheless.

Fiedler, C.E.; Friederici, P.; Petruncio, M.; [et al.]. 2007. Managing for old growth in frequent-fire landscapes. *Ecology and Society*. 12(2): 20. <https://www.jstor.org/stable/26267898>

•Fiedler, C.E.; Metlen, K.L.; Dodson, E.K. 2010. Restoration treatment effects on stand structure, tree growth, and fire hazard in a ponderosa pine/Douglas-fir forest in Montana. *Forest Science*. 56(1): 18–31. <https://doi.org/10.1093/forestscience/56.1.18>

Value: This research article introduces the treatments implemented on the Lubrecht Experimental Forest, described in chapter 8 of this guide. This article presents a useful illustration of how the modified thinning and prescribed burning treatments implemented at Lubrecht for fuel reduction purposes can be designing to achieve restoration objectives as part of a silvicultural system for transformation to multi-aged structures.

Foiles, M.W.; Curtis, J.D. 1973. Regeneration of ponderosa pine in the northern Rocky Mountain-Intermountain Region. Res. Paper INT-145. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 45 p.

Forrester, D.I.; H. Schmid, H.; Nitzsche, J. 2022. Growth and structural changes in Swiss uneven-aged forests over 100 years, and comparisons between 15 uneven-aged forest types of Europe, North America and Australia. *Forestry* 95(2): 166–186.

Franklin, J.F.; Berg, D.F.; Thornburg, D. [et al.]. 1997. Alternative silvicultural approaches to timber harvesting: Variable retention harvest systems. In: Kohm, K.A.; Franklin, J.F., eds. *Creating a forestry for the 21st century: The science of ecosystem management*. Washington, DC: Island Press: 111–140.

Franklin, J.F., K.N. Johnson, and D.L. Johnson. 2018. Ecological forest management. Long Grove, IL: Waveland Press. 646 p.

Fryer, Janet L. 2018. *Pinus ponderosa* var. *benthamiana*, *P. p.* var. *ponderosa*: Ponderosa pine. In: Fire Effects Information System, [Online]. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory. www.fs.usda.gov/database/feis/plants/tree/pinponp/all.html

Goodburn, J.M.; Lorimer, C.G. 1999. Population structure in old-growth and managed northern hardwoods: An examination of the balanced diameter distribution concept. *Forest Ecology and Management*. 118(1-3): 11–29.

•Graham, R.T.; Jain, T.B. 2005. Application of free selection in mixed forests of the Inland Northwestern United States. *Forest Ecology and Management*. 209(1–2): 131–145.

<https://doi.org/10.1016/j.foreco.2005.01.019>

•Graham, R.T.; Jain, T.B.; Sandquist, J. 2006. Free selection: A silvicultural option. In: Powers, Robert F., tech. ed. *Restoring fire-adapted ecosystems: Proceedings of the 2005 National Silviculture Workshop: Gen. Tech. Rep. PSW-GTR-203*. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. p. 121–156. <https://research.fs.usda.gov/treearch/25897> [Accessed 29 May 2025]

Value: These two articles provide the most detailed conceptual and practical guidance for designing and implementing the free selection system and free selection harvests. The content covers both treatment implementation and developing the guiding vision that underpins free selection. Lessons and advice for the use of free selection are provided. The content of these two papers is similar.

Greenler, S.M.; Dunn, C.J.; Johnston, J.D.; [et al.]. 2023. Too hot, too cold, or just right: Can wildfire restore dry forests of the interior Pacific Northwest? *Plos One* 18(2): p.e0281927. <https://doi.org/10.1371/journal.pone.0281927>

•Guldin, J.M.; Baker, J.D. 1998. Uneven-aged silviculture, southern style. *Journal of Forestry* 96(7): 22–26. <https://doi.org/10.1093/jof/96.7.22>

Value: This short article is probably the best widely-accessible resource for the volume control-guiding diameter limit method of stocking control in multi-aged stands, and also describes use of the BDq method of stocking control. A strength of this article is the practical ideas for improving feasibility of these two methods of stocking control.

Gustafsson, L.; Baker, S.C.; Bauhus, J.; [et al.]. 2012. Retention forestry to maintain multifunctional forests: A world perspective. *BioScience*. 62(7): 633–645. <https://doi.org/10.1525/bio.2012.62.7.6>

Hagle, S.K.; Gibson, K.E.; Tunnock, S. 2003. Field guide to disease and insect pests of northern and central Rocky Mountain conifers. Report No. R1-03-08. (Reprinted in 2013 with minor revisions; B.A. Ferguson, Montana DNRC Ed.). Missoula, MT, and Ogden, UT: U.S. Department of Agriculture, State and Private Forestry, Northern and Intermountain Regions. 197 p. https://dnrc.mt.gov/docs/forestry/Forestry_Assistance/Forest_Pests/2013-A-FIELD-GUIDE-TO-insect-and-disease-as-PDF.pdf [Accessed 29 May 2025]

- Hagmann, R.K.; Franklin, J.F.; Johnson, K.N. 2013. Historical structure and composition of ponderosa pine and mixed-conifer forests in south-central Oregon. *Forest Ecology and Management*. 304: 492–504. <https://doi.org/10.1016/j.foreco.2013.04.005>
- Hagmann, R.K.; Hessburg, P.F.; Prichard, S.J.; [et al.]. Evidence for widespread changes in the structure, composition, and fire regimes of western North American forests. *Ecological Applications* 31(8): e02431. <https://doi.org/10.1002/eap.2431>
- Hallin, W.E. 1959. The application of unit area control in the management of ponderosa-Jeffrey pine at Blacks Mountain Experimental Forest. Tech. Bull. 1191. Washington, DC: U.S. Department of Agriculture, Forest Service. 96 p.
- Halofsky, J.E.; Peterson, D.L. Dante-Wood, S.K.; [et al.], eds. 2018. Climate change vulnerability and adaptation in the northern Rocky Mountains. [Part 1.]. Gen. Tech. Rep. RMRS-GTR-374. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 1–273. <https://doi.org/10.2737/RMRS-GTR-374PART1>
- Harrington, M.G.; Hawksworth, F.G. 1990. Interactions of fire and dwarf mistletoe on mortality of southwestern ponderosa pine. In: Krammes, J.S., tech. coord. Effects of fire management of southwestern natural resources, Proceedings of the Symposium; 1998 Nov. 15–17; Tucson, AZ . Gen. Tech. Rep. GTR-RM-191. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 234–293.
- Hawksworth, F.G. 1961. Dwarf mistletoe of ponderosa pine in the Southwest. Tech. Bull. 1246. Washington, DC: U.S. Department of Agriculture, Forest Service. 119 p.
- Hawksworth, Frank G. 1977. The 6-class dwarf mistletoe rating system. Gen. Tech. Rep. GTR-RM-48. Fort Collins, Co: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 7 p.
- Helms, J.A. 1980. The California region. In: Barret, J.W. ed. Regional silviculture of the United States, second edition. New York: John Wiley and Sons: 441–498.
- Hessburg, P.F.; Agee, J.K.; Franklin, J.F. 2005. Dry forests and wildland fires of the Inland Northwest USA: Contrasting the landscape ecology of the pre-settlement and modern eras. *Forest Ecology and Management*. 211(1–2): 117–139. <https://doi.org/10.1016/j.foreco.2005.02.016>
- Hessburg, P.F.; Povak, N.A.; Salter, R.B. 2008. Thinning and prescribed fire effects on dwarf mistletoe severity in an eastern Cascade Range dry forest, Washington. *Forest Ecology and Management*. 255: 2907–2915. <https://doi.org/10.1016/j.foreco.2008.01.066>
- Hessburg, P.F.; Churchill, D.A.; Larson, A.D; [et al.]. 2015. Restoring fire-prone Inland Pacific Landscapes: Seven core principles. *Landscape Ecology*. 30: 1805–1835. <https://doi.org/10.1007/s10980-015-0218-0>
- Hessburg, P.F.; Miller, C.L.; Parks, S.A.; [et al.]. 2019. Climate, environment, and disturbance history govern resilience of western North American forests. *Frontiers in Ecology and Evolution* 7: 239. <https://doi.org/10.3389/fevo.2019.00239>

Hoffman, C.; Mathiasen, R.; C.H. Sieg, C.H. 2007. Dwarf mistletoe effects on fuel loadings in ponderosa pine forests in northern Arizona. Canadian Journal of Forest Research. 37(3): 662–670. <https://doi.org/10.1139/X06-259>

Howard, Janet L. 2003. *Pinus ponderosa* var. *brachyptera*, *P. p.* var. *scopulorum*. In: Fire Effects Information System, [Online]. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer). www.fs.usda.gov/database/feis/plants/tree/pinpons/all.html

Hood, S.M. 2010. Mitigating old tree mortality in long-unburned, fire-dependent forests: A synthesis. Gen. Tech. Rep. RMRS-GTR-238. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 71 p. <https://doi.org/10.2737/RMRS-GTR-238>

••Hood, S.M.; Keyes, C.R.; Bowen, K.J.; [et al.]. 2020. Fuel treatment longevity in ponderosa pine-dominated forest 24 years after cutting and prescribed burning. *Frontiers in Forests and Global Change* 3: 78. <https://doi.org/10.3389/ffgc.2020.00078>

Value: This article provides 24-year post-harvest structure for the irregular shelterwood study at Lick Creek, including overstory, regeneration and fuels, accompanied by interpretation of these medium-term post-treatment changes. Although this is written for a research audience, the quantitative stand structure data is extremely useful for informing expectations of irregular shelterwood harvests implemented in stands with similar structure to those described in the article. The discussion of fuel treatment effectiveness can also be used to inform development of cutting cycles for stands in similar *Pseudotsuga menziesii* habitat types.

Hood, S.M.; Harvey, B.J.; Fornwalt, P.J.; [et al.]. C.E. 2021. Fire ecology of Rocky Mountain forests[Chapter8]. In: Greenberg, C.H., Collins, B., eds. *Fire ecology and management: Past, present, and future of U.S. forested ecosystems*. Vol. 39 Cham, Switzerland: Springer Cham: 287–336. https://doi.org/10.1007/978-3-030-73267-7_8

Hood, S.M.; Varner, J.M.; Jain, T.B.; [et al.]. 2022a. A framework for quantifying forest wildfire hazard and fuel treatment effectiveness from stands to landscapes. *Fire Ecology*. 18(1): 1–12. <https://doi.org/10.1186/s42408-022-00157-0>

Hood, S.M.; Schaupp Jr., W.C.; Goheen, D.J. 2022b. Radial thinning ineffective at increasing large sugar pine survival. *Forest Ecology and Management*. 520: 120351. <https://doi.org/10.1016/j.foreco.2022.120351>

••Hood, S.M.; Crotteau, J.S.; Cleveland, C.C. 2024. Long-term efficacy of fuel reduction and restoration treatments in Northern Rockies dry forests. *Ecological Applications*. 34: 2 e2940. <https://doi.org/10.1002/eap.2940>

Value: This research publication summarizes changes in stand structure, plant communities, carbon storage, and soil nutrients two decades after the treatments implemented at Lubrecht Experimental Forest (see Fiedler et al., 2010, above). The paper is primarily written for a research audience, and through a lens of fuel treatment effectiveness rather than transformation, but the summary tables that it contains may be informative for foresters interested in a broad understanding of the potential ramifications of cut and burn, cut-only and burn-only treatments implemented with a transformation and restoration basis, as much as for fuel reduction purposes.

Huffman, D.W.; Roccaforte, J.P.; Springer, J.D.; [et al.]. 2020. Restoration applications of resource objective wildfires in western U.S. forests: A status of knowledge review. *Fire Ecology*. 16: 1–13. <https://doi.org/10.1186/s42408-020-00077-x>

Irving, F.D.; French, D.W. 1971. Control by fire of dwarf mistletoe in black spruce. *Journal of Forestry*. 69(1): 28–30. <https://doi.org/10.1093/jof/69.1.28>

Isaac, L.A. 1967. Douglas-fir research in the Pacific Northwest, 1920–1956. Interview by A.R. Fry. University of California, Bancroft Library, Regional Oral History Office, Berkeley, CA.

•Jain, T.B.; Battaglia, M.A.; Han, H.S. 2012. A comprehensive guide to fuel management practices for dry mixed conifer forests in the northwestern United States. Gen. Tech. Rep. RMRS-GTR-292. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 331 p. <https://doi.org/10.2737/RMRS-GTR-292>

Value: This Forest Service general technical report is among the most comprehensive practical resources for fuels management, so has high value as an aid to designing treatments to reduce fire hazard in multi-aged stands and should also help in the design of structures that minimize fire hazard.

Jain, T.B.; Sikkink, P.; Keefe, R. [et al.]. 2018. To masticate or not: Useful tips for treating forest, woodland, and shrubland vegetation. Gen. Tech. Rep. RMRS-GTR-381. Fort Collins, CO; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 55 p. <https://doi.org/10.2737/RMRS-GTR-381>

Jain, T.B.; Graham, R.T.; Byrne, J.C. 2020. Canopy opening and site preparation effects on conifer and understory establishment and growth after an uneven-aged free selection regeneration harvest in the northern Rocky Mountains, USA. *Forests*. 11(6): 622. <https://doi.org/10.3390/f11060622>

Janowiak, M.K.; Nagel, L.M.; C.R. Webster. 2008. Spatial scale and stand structure in northern hardwood forests: Implications for quantifying diameter distributions. *Forest Science*. 54(5): 497–506. <https://doi.org/10.1093/forestscience/54.5.497>

Johnson, P.C. 1966. Some causes of natural tree mortality in old-growth ponderosa pine stands in western Montana. Res. Note INT-RN-51. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 6 p.

Johnson, D.W. 1986. Comandra blister rust. Forest Insect & Disease Leaflet FIDL 62. Revised 1986. Washington, DC: U.S. Department of Agriculture, Forest Service. FIDL 62. 8 p. <https://www.fs.usda.gov/foresthealth/docs/fidls/FIDL-62-ComandraBlisterRust.pdf> [Accessed 29 May 2025]

Johnston, J.D. 2017. Forest succession along a productivity gradient following fire exclusion. *Forest Ecology and Management*. 392: 45–57. <https://doi.org/10.1016/j.foreco.2017.02.050>

Kane, V.R.; Bartl-Geller, B.N.; North, M.P. [et al.]. 2019. First-entry wildfires can create opening and tree clump patterns characteristic of resilient forests. *Forest Ecology and Management*. 454: 117659. <https://doi.org/10.1016/j.foreco.2019.117659>

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<https://doi.org/10.1016/B978-0-12-384719-5.00389-0>
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Value: Although this research paper contains some highly technical material that is unlikely to be immediately relevant to most practitioners, skip to Section 2.6 for the clearest articulation of the development of spatial patterns in ponderosa pine (and dry mixed-conifer) forests that we are aware of. Practitioners looking to incorporate complex spatial patterns into the design of silvicultural treatments should also review the practical recommendations in Section 4.2.

Larson, A.J.; Belote, R.T.; Cansler, C.A. [et al.]. 2013. Latent resilience in ponderosa pine forest: Effects of resumed frequent fire. *Ecological Applications*. 23(6): 1243–1249. <https://doi.org/10.1890/13-0066.1>

••Larson, A.J.; Churchill, D.J. 2023. Ecological silviculture for interior ponderosa pine and dry mixed-conifer ecosystems. In: Palik, B.J.; D’Amato, A.W., eds. *Ecological silvicultural systems: Exemplary models for sustainable forest management*. Hoboken, NJ: John Wiley and Sons, Inc.: 184–198.

Value: See also Churchill, 2021. These excellent accounts discuss the structure and developmental processes of forests with a historic frequent to moderately frequent fire regime. The authors then use the ecological silviculture framework to develop treatment options for producing resilient stand structures associated with forests with an intact disturbance regime. In this, they apply a similar condition-based approach that is used here in RMRS-GTR-446.

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- Value:** These two short research articles provide stepwise instructions for using the SDI-allocation method of stocking control to design multi-aged structures and plan multi-aged treatments. They are not practical guides for on-the-ground treatment implementation, but the worked examples are from ponderosa pine forests. These articles are written and structured in an accessible form and their content is similar.
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 - Long, J.N.; Smith, F.W. 2000. Restructuring the forest: Goshawks and the restoration of southwestern ponderosa pine. *Journal of Forestry*. 98(8): 25–30. <https://doi.org/10.1093/jof/98.8.25>
- Value:** See also Youtz et al. (2008). These two publications provide conceptual and practical advice for using a condition-based, area control stocking control method for silvicultural transformation and multi-aged management in ponderosa pine forests. Both articles, and especially Youtz et al. (2008), include good advice for implementation on-the-ground using the example of converting relatively uniform ponderosa pine stands into more complex structures, at stand to meso-scales, to provide habitat for northern goshawk (*Accipiter gentilis*).
- Lorimer, C.G.; Frelich, L.E. 1997. A structural alternative to chronosequence analysis for uneven-aged northern hardwood forests. *Journal of Sustainable Forestry*. 6(3–4): 347–366.
- Maher, C.T., Oja, E.; Marshall, A.; [et al.]. 2019. Real-time monitoring with a tablet app improves implementation of treatments to enhance forest structural diversity. *Journal of Forestry*. 117(3): 280–292. <https://doi.org/10.1093/jofore/fvz003>
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••McIntyre, R.K.; Jack, S.B.; Mitchell, R.J.; [et al.]. 2008. Multiple value management: The Stoddard-Neel approach to ecological forestry in longleaf pine grasslands. Newton, GA: The Jones Center at Ichauway. 30 p. <https://doi.org/10.58497/74641>

Value: See also Mitchell et al (2006). These two publications are excellent resources for application of the Stoddard-Neel Approach (SNA) to stocking control in multi-aged stands where the natural disturbance regime includes frequent to moderately frequent fire. Mitchell et al. (2006) provides a more advanced discussion of the SNA and compares it to other stocking control approaches, such as the BDq system, but still contains useful practical information to guide treatment implementation and much of the general approach to the SNA described here can be used to inform application of other individual tree evaluation stocking control methods. McIntyre et al. (2008) is the more practical resource and also contains useful case studies. Both of these publications are written with a focus on longleaf pine forests, but many concepts and applications can be transferred to ponderosa pine forests.

McKinney, S.T.; Abrahamson, I.; Jain, T.; [et al.]. 2022. A systematic review of empirical evidence for landscape-level fuel treatment effectiveness. *Fire Ecology*. 18, Article number: 21. <https://doi.org/10.1186/s42408-022-00146-3>

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Meyer, W.H. 1934. Growth in selectively cut ponderosa pine forests in the Pacific Northwest. Technical Bulletin Tech. Bull. 407. Washington DC: U.S. Department of Agriculture, Forest Service. 73 p.

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Value: See also McIntyre et al (2008). These two publications are excellent resources for application of the Stoddard-Neel Approach (SNA) to stocking control in multi-aged stands where the natural disturbance regime includes frequent to moderately frequent fire. Mitchell et al. (2006) provides a more advanced discussion of the SNA and compares it to other stocking control approaches, such as the BDq system, but still contains useful practical information to guide treatment implementation and much of the general approach to the SNA described here can be used to inform application of other individual tree evaluation stocking control methods. McIntyre et al. (2008) is the more practical resource and also contains useful case studies. Both of these publications are written with a focus on longleaf pine forests, but many concepts and applications can be transferred to ponderosa pine forests.

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<https://doi.org/10.1016/j.foreco.2021.120004>
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Value: This relatively short textbook is the definitive guide to multi-aged silviculture, so is a go-to resource for silvicultural transformation and subsequent long-term multi-aged management. The section on silvicultural transformation itself is relatively short, but helpful. If reading the section on stocking control, note that O'Hara describes the LAI-allocation method that he pioneered. This method has many strengths, but we do not include it here in RMRS-GTR-446 because implementation is only practical when accompanied by a spreadsheet-based LAI calculation and distribution tool that is not publicly available.

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<https://doi.org/10.1016/j.foreco.2005.12.036>

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Value: This technical report is not specifically developed around ponderosa pine or transformation, but remains one of the best resources for transformation because of its accessibility, breadth and practicality on topics relating to implementation of uneven-aged management. This includes the advantages and disadvantages of uneven-aged management, the situations in which uneven-aged management may be suitable, and practical advice for implementation. The document also provides an excellent worked example of single-tree selection using the BDq system of stocking control in a mixed-conifer stand. The document does have important limitations. The content is written primarily for uneven-aged structures rather than two-aged structures, and the emphasis is on the classic selection-based uneven-aged harvest methods and the BDq system of stocking control, rather than a broader treatment of harvest methods and stocking control concepts. This perspective is reflected in its framing of the advantages and disadvantages of uneven-aged management, discussion of the sites on which uneven-aged management might be suitable, and elsewhere in the report. Therefore, this technical report is best read after first working through the broader discussion of more flexible multi-aged management options presented here in RMRS-GTR-446. Notwithstanding these limitations, Powell et al. (2018) is an extremely useful and practical resource.

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Value: See also Long and Smith (2000). These two publications provide conceptual and practical advice for using a condition-based, area control stocking control method for silvicultural transformation and multi-aged management in ponderosa pine forests. Both articles, and especially Youtz et al. (2008), include good advice for implementation on-the-ground using the example of converting relatively uniform ponderosa pine stands into more complex structures, at stand to meso-scales, to provide habitat for northern goshawk (*Accipiter gentilis*).

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