14

Ecological Silviculture for Interior Ponderosa Pine and Dry Mixed-Conifer Ecosystems

Andrew J. Larson[1] and Derek J. Churchill[2]

[1] *Department of Forest Management, University of Montana, Missoula, MT, USA*
[2] *Forest Resilience Division, Washington Department of Natural Resources, Olympia, WA, USA*

14.1 Introduction

Interior western ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) and dry mixed-conifer ecosystems with a major ponderosa pine component are the focus of this chapter. These forests are found throughout the interior western United States from Arizona and New Mexico north to southern interior British Columbia, Canada, and extend east into the island ranges of the western Great Plains. Mixed-conifer and mixed-evergreen ecosystems with a minor ponderosa pine component occur in southwestern Oregon, California, and in northwestern Mexico, but they are beyond the scope of this chapter.

This ecosystem was managed for grazing and timber extraction beginning with widespread Euro-American settlement in the middle 1800s [1]. Fire suppression became a management focus after 1905 with the formation of the United States Forest Service. Early twentieth century harvest focused on selective removal of large diameter "overmature" pines (Figure 14.1). In the post-WWII period, this gave way to intensive forestry practices, including even-aged silvicultural systems based on clear-cutting and plantations that were optimized for timber production. This agricultural model of forest management excluded frequent fire, the keystone disturbance process that maintains open, multi-age forests dominated by large, fire-resistant trees.

This chapter establishes the ecological basis and silvicultural strategies to implement ecological silviculture in these ecosystems. The overall objective is to manage conditions that are resilient to wildfire, drought, bark beetles, and other stressors while sustaining native biodiversity and providing for an array of ecosystem services, including wood production. It is a long-term, multi-age silvicultural system that includes considerations for reintroduction of frequent fire, regeneration of fire- and drought-resistant species, and climate change adaptation. Stand-level ecological silviculture in this forest type will be most effective at reducing wildfire risk, enhancing ecosystem resilience and adaptive capacity, and sustaining native biodiversity when implemented as part of a large landscape strategy [2].

Ecological Silvicultural Systems: Exemplary Models for Sustainable Forest Management, First Edition. Edited by Brian J. Palik and Anthony W. D'Amato.

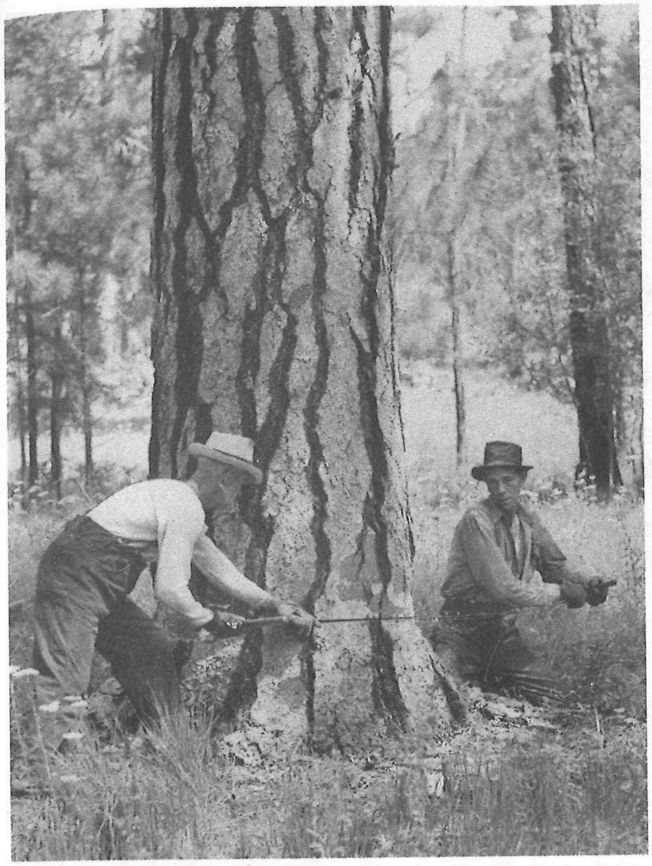


Figure 14.1 Felling a large diameter ponderosa pine using a crosscut saw Colville Indian Reservation, Washington. Original caption, "Felling crew at work on the Katar unit, ca. 7/1942." *Source:* Harold Weaver/ U.S. National Archives and Records Administration (NARA)/Wikimedia Commons/Public Domain.

14.2 Characteristics of Ponderosa Pine and Dry-Mixed Conifer Ecosystems

14.2.1 Composition and Structure

Large-diameter trees of fire-resistant species, often ranging in age from 120 to >400 years, comprise most of the basal area of active fire regime sites (Figures 14.2 and 14.3). Canopy cover is low, typically ranging from 15% to 35% averaged across entire stands (Figure 14.3). Basal areas are similarly low, ranging from about 5–25 m^2 ha^{-1}. Spatial heterogeneity in tree locations (Figure 14.4) is expressed in the characteristic pattern of widely spaced individual trees, tree clumps, and canopy openings of variable shape and size – a mosaic of small patches (about 0.02–0.5 ha) of different structural conditions [3]. Large-diameter standing snags and downed logs are other important structural features.

Pure or nearly pure ponderosa pine stands are common in the southwestern and Black Hills and Great Plains regions of the United States, while mixed-species stands of ponderosa pine, Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Mayr), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.)

Figure 14.2 A dry mixed-conifer forest dominated by large, old, fire-resistant trees in western Montana managed by The Nature Conservancy using ecological silviculture and prescribed fire. *Source:* Andrew J. Larson.

or white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), western larch (*Larix occidentalis* Nutt.), and lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) are more common in the northern Rocky Mountains and Inland Pacific Northwest (Table 14.1). Additional species can be present in limited abundance, including broadleaf species such as oaks and aspen that provide important habitat value.

Ponderosa pine and dry mixed-conifer ecosystems are typically embedded in landscapes that include dry woodlands and rangelands at lower elevations and moist or cold conifer forests at middle to higher elevations [2]. In mountainous terrain, these vegetation communities and fire regimes may occur in close juxtaposition, for example, a switch from dry mixed-conifer ecosystems on south and west aspects to moist or cold mixed-conifer ecosystems that burned less frequently but with higher severity on adjacent north and east aspects.

14.2.2 Disturbance Regime

The disturbance regime is characterized by frequent surface fire that resulted from extensive Native American burning and lightning ignitions [1]. Mean fire return intervals range from about 5 to 20 years but on some colder, low-productivity sites return intervals may approach 50 years. Occasional mixed- and high-severity fires did occur but were a minor component of the historical fire regime. Bark beetles, especially the mountain pine beetle, western pine beetle, and Douglas-fir beetle (*Dendroctonous* species), are another important disturbance agent, with periodic outbreaks occasionally causing widespread overstory tree mortality.

Frequent surface fire functions as a stabilizing feedback mechanism, maintaining forest structure through successive fire events [4]. By consuming surface fuels, thinning small regenerating

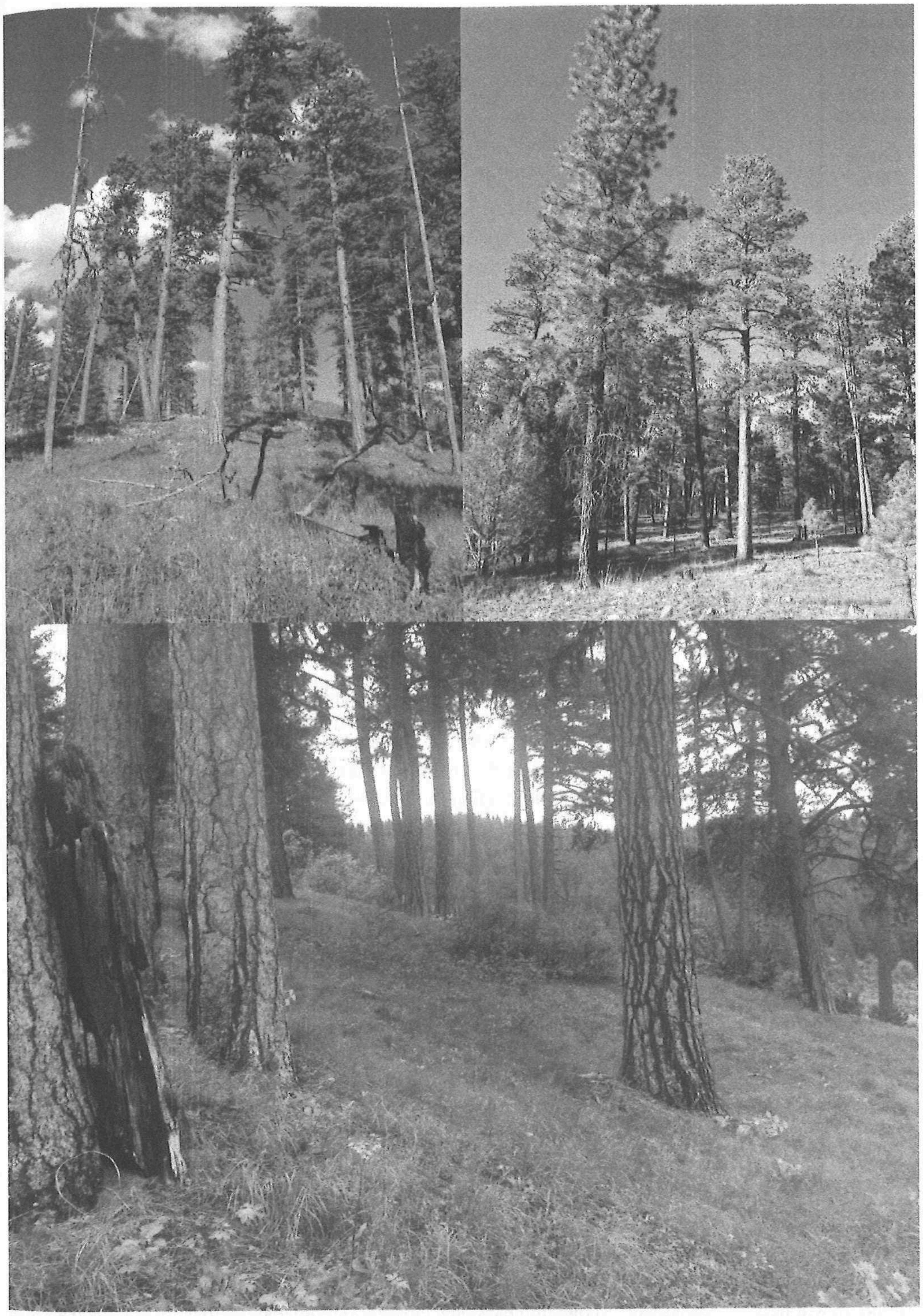


Figure 14.3 Structural conditions in contemporary active frequent fire regime ponderosa pine/mixed-conifer ecosystems, Bob Marshall Wilderness, Montana (top left), Kaibab National Forest, Arizona (top right), and Selway-Bitterroot Wilderness, Idaho (bottom), USA. *Source:* Photos by Andrew J. Larson (top row) and Mark R. Kreider (bottom).

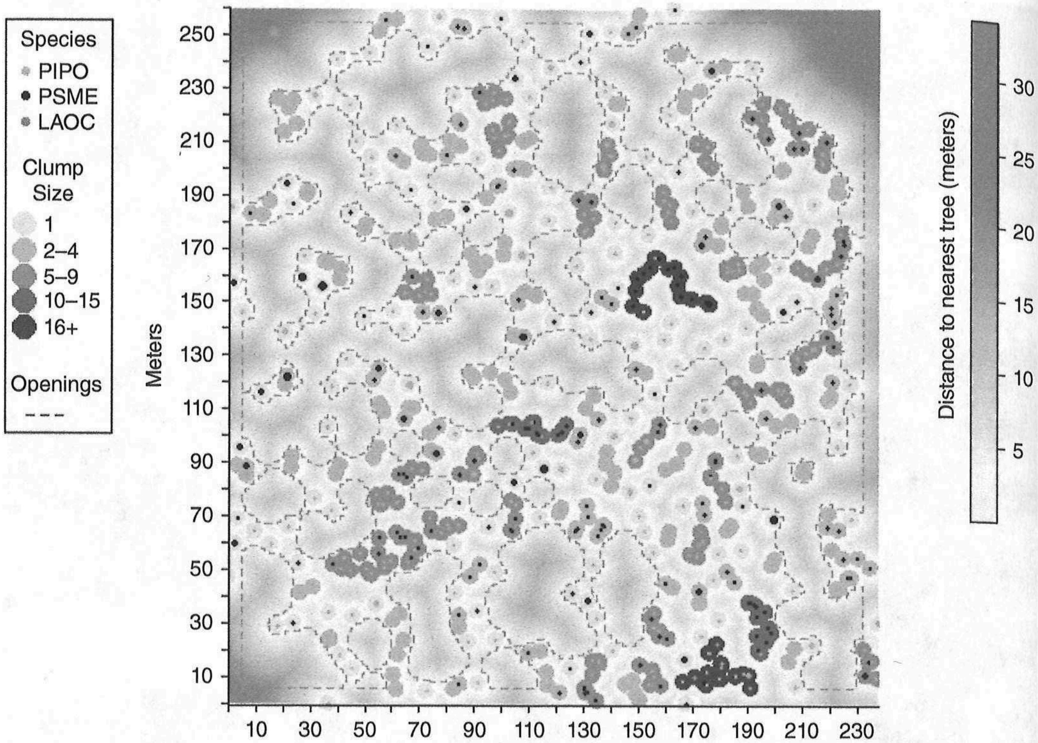
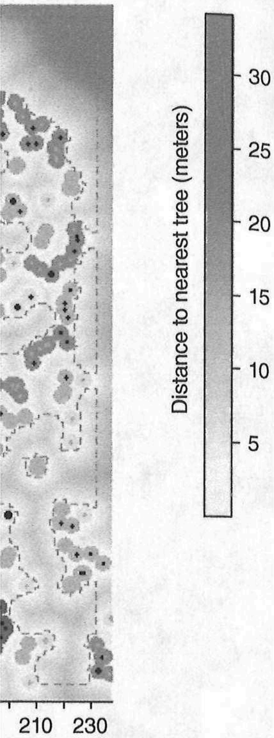


Figure 14.4 Stem map showing the mosaic stand structure of individual trees, tree clumps of various sizes, and openings in a dry ponderosa pine/Douglas-fir ecosystem, eastern Cascade Range, Washington, USA.

Table 14.1 Major conifer tree species and their key characteristics.

Species	Drought resistance	Fire resistance and resilience	Preferred seed bed	Shade tolerance	Max life span (yrs)
Ponderosa pine (*Pinus ponderosa*)	High	Very high: rapid development of thick bark, protected buds, deep roots, resinous wood, high crown base	Mineral	Intolerant	800+
Douglas-fir (*Pseudotsuga menziesii* var. *glauca*)	High	Moderate: develops thick bark with age; intermediate crown base height	Mineral and organic	Moderately tolerant	600+
Western larch (*Larix occidentalis*)	Moderate	High to very high: develops thick bark with age, deciduous, vigorous epicormic sprouter, high crown base	Mineral	Intolerant	700+
Grand fir/white fir (*Abies grandis*/*A. concolor*)	Moderate	Low: thin bark, low crown base, relatively shallow roots	Organic	Tolerant	400+



tree clumps of various sizes,
Range, Washington, USA.

Shade tolerance	Max life span (yrs)
Intolerant	800+
Moderately tolerant	600+
Intolerant	700+
Tolerant	400+

trees, and pruning lower branches, forest structure is maintained in a low potential energy (i.e. low fuel loading), fire-resistant state. When fires occur, the energy released is insufficient to kill most overstory trees, and crown fire initiation and spread are unlikely [5].

14.2.3 Developmental Model

Ponderosa pine and dry mixed-conifer ecosystems seldom progress through the linear structural development stages common in other forest types (e.g. [6]) due to the rarity of stand-replacement disturbances. Most structural conditions and developmental processes are present, but they occur as a mosaic (Figure 14.4) of small patches (0.02–0.5 ha) instead of more uniform conditions across large areas typical of stand-replacement disturbance regimes. Forest development is presented in [3], with additional detail in [7]. We summarize the key elements here.

The developmental sequence initiates with spatially aggregated tree seedling establishment in canopy openings. Dense thickets of seedlings establish on exposed mineral soil that results from surface fires consuming downed logs that are the result of prior mortality of individual or groups of large trees. This seedbed provides temporary refuge from future surface fires due to scarified soil and consumed fine fuels, as well as reduced competition with understory plants. Tree seedling establishment also occurs at low densities throughout the open forest.

As trees in regeneration clumps grow, they undergo thinning by subsequent fires and density dependent mortality. Over time, tree clumps continue to be thinned by recurring fires, endemic bark beetle attacks, and other agents that cause mortality of individuals or small groups of trees. The developmental cycle continues as individuals and groups of old trees die and eventually fall to the ground, and are consumed in future fires, creating new mineral soil-safe sites for seedlings of fire-resistant species to establish. Repetition of fires, tree regeneration, and mortality of individuals and small groups of trees perpetuates a shifting, fine-scale mosaic of tree clumps and openings in different stages of development [3], with density maintained well below maximum stocking, generally <30% of maximum stand density index [8]. This low-competition environment promotes resilience to fires, drought, and bark beetle attacks.

14.3 An Ecological Silvicultural System for Ponderosa Pine and Dry-Mixed Conifer Ecosystems

Current conditions in ponderosa pine and mixed-conifer forests vary widely based on management history, productivity, and other factors. Foresters implementing this system will often start with stands that are highly departed from the natural developmental model due to past fire exclusion and harvest, where the first order of business is to shift composition and structure to conditions that can be managed sustainably over the long term. In forests that are closer to the natural model (Figure 14.2), multi-age treatments that mimic the natural disturbance regime are utilized.

An ecological silviculture system for ponderosa pine and dry mixed-conifer ecosystems with frequent, low-severity fire regimes is included in detail elsewhere [7]; here we summarize the major elements (Box 14.1). These elements are applicable to all structural conditions and prescriptions, but forest managers may choose to emphasize them to different degrees depending on the initial condition of each management unit (Table 14.2).

Box 14.1 Elements of an Ecological Silviculture System for Ponderosa Pine and Dry Mixed-Conifer Ecosystems

1) **Regeneration of fire-tolerant tree species.** Regeneration of fire-resistant species is critical to the long-term management of frequent-fire forests. This is especially true for shade-intolerant ponderosa pine and western larch, which have a strong affinity for mineral soil seedbeds created by fire. Establishing clumps of regeneration (groups of 10 to >100 trees) in small to medium-sized openings (0.02–0.5 ha) will set stands on a trajectory towards the desired fine-scale, multi-cohort, spatial mosaic. In general, different cohorts should be spatially segregated with smaller trees rarely growing underneath larger trees where they act as ladder fuels. Mechanical scarification during harvests, prescribed fire, or both can be utilized to promote natural regeneration in openings. Planting may be needed to achieve the desired composition, density, and spatial pattern.
2) **Recruitment and perpetuation of large and old trees.** Large diameter trees, which are often old (>150 years), fulfill an array of ecosystem functions and services: they are fire resistant due to thick bark and high crown bases, store most of the aboveground carbon, contribute disproportionately to seed production, and produce large quantities of leaf litter to carry surface fires. Large, old trees develop decadence – dead tops, heart rot, cavities, and complex branches and crown architecture – features that make them especially valuable as wildlife habitats (Figure 14.5). Perpetuation of large tree populations does not preclude harvest or wood production objectives.
3) **Retention of some dying and dead large-diameter trees as snags and logs.** Large-diameter dead wood provides essential habitat for biodiversity (Figure 14.5) and contributes to

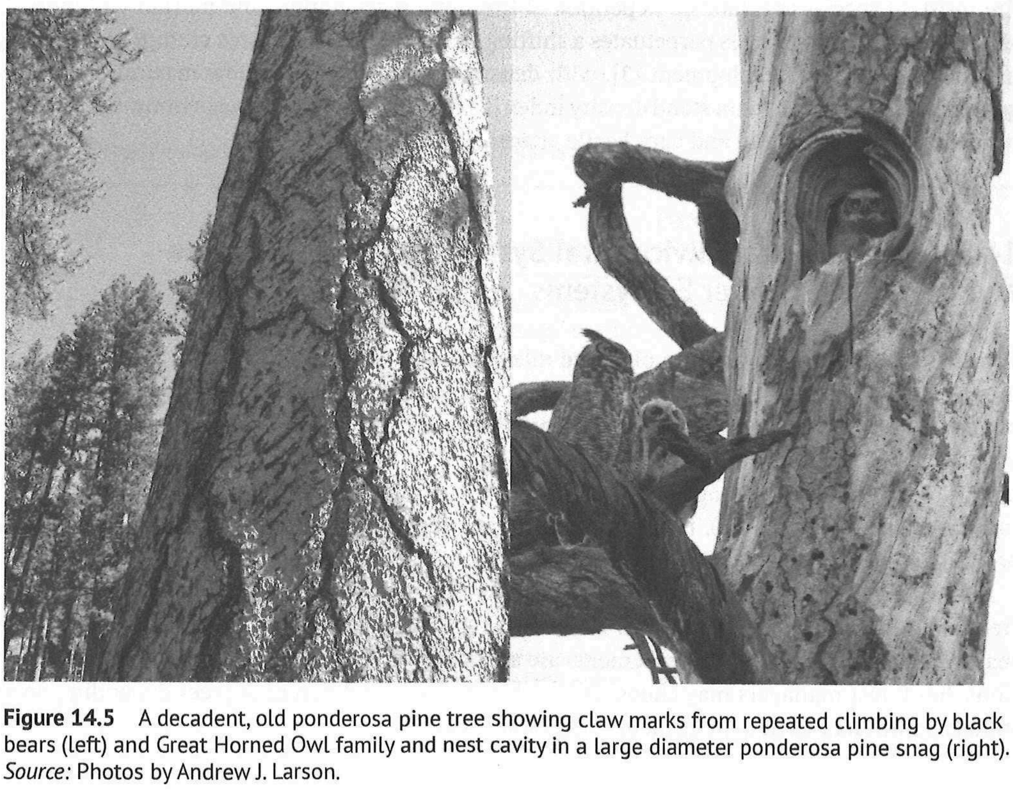


Figure 14.5 A decadent, old ponderosa pine tree showing claw marks from repeated climbing by black bears (left) and Great Horned Owl family and nest cavity in a large diameter ponderosa pine snag (right). *Source:* Photos by Andrew J. Larson.

small-scale variation in fire behavior and effects as long-burning, heavy fuels. Leaving some larger trees to die and fulfill these ecological functions is a necessary component of an ecological silviculture system in frequent-fire forests.

4) **Maintenance of low tree density with few ladder fuels.** Low stand density (i.e. low crown bulk density) provides resistance to drought and crown fire spread. Minimizing multistory conditions–trees growing underneath other trees – by thinning understory and midstory trees reduces likelihood of crown fire initiation by maintaining separation between surface fuels and the canopy. Prescribed fire can be an effective tool to reduce ladder fuels and increase crown base height (Figure 14.6). Retaining denser clumps of small trees in canopy openings is important, however.
5) **Perpetuation of a fine-grained spatial mosaic.** Restoring and managing for a multi-cohort patch structure of individual trees, tree clumps, regeneration thickets, and openings perpetuates the natural forest development model in managed forests [2, 3, 9], as well as habitat, snow retention, plant diversity, and other ecosystem functions [10]. Patch sizes should generally range from about 0.02 to 0.5 ha, although patches may be larger in some cases (e.g. 1–2 ha).
6) **Maintenance of surface fuel loads conducive to low-severity fire.** Prescribed fire is the most effective tool for reducing surface fuel loads and keeping them low over time (Figure 14.6). Other methods like piling and burning or mastication can be used when prescribed fire is not feasible. If surface fuel loads are too great even low-density, large tree-dominated forests are at risk of stand replacement fire effects during wildfires.
7) **Maintenance of native understory plant communities and broadleaf tree species.** Understory plants represent the majority of plant species diversity and contribute important ecosystem functions including nitrogen fixation that are not provided by the conifer overstory. Herbaceous plants, especially grasses, are a source of fine fuels that carry surface fires under an active frequent fire regime. In these conifer ecosystems, insect and pollinator communities rely on the flowering understory plants, as do wildlife species, including ungulate grazers and browsers.

Figure 14.6 Conditions during (left) and after (right) prescribed fire treatment in dry ponderosa pine/mixed-conifer ecosystems, western Montana, USA. *Source:* Andrew J. Larson.

Table 14.2 Example structural conditions and potential ecologically based silvicultural treatments in ponderosa pine and dry mixed-conifer ecosystems.

Condition	Potential silvicultural activities[a]
1) High density even-aged	• Commercial and/or non-commercial variable-density thinning (VDT), with explicit guidelines to create spatial variability. • Prescribed (Rx) fire or mechanical fuel treatment to reduce surface fuels and create regeneration opportunities.
2) High-density multi-cohort with fire- and drought-tolerant trees	• Species and size-based commercial and/or noncommercial VDT with explicit guidelines to create spatial variability. • Rx fire or mechanical fuel treatment to reduce surface fuels and create regeneration opportunities.
3) High density with few healthy fire- and drought-resistant trees	• Variable retention harvest to create opportunities for planting, while retaining healthy, fire-resistant trees and large diameter snags. • Rx fire or pile burning to reduce surface fuels. • Plant climate-adapted, fire- and drought-resistant trees to achieve desired species composition and spatial pattern.
4) a. Recently burned by moderate-severity wildfire	• Harvest green and dead trees to further shift composition and structure to large trees of fire- and drought-resistant species and to reduce future surface fuel accumulation while retaining sufficient dead trees for habitat and other ecological values. • Monitor natural regeneration and plant or thin in future if needed.
b. Recently burned by high-severity wildfire	• Harvest dead trees to manage future fuel accumulation while retaining live trees and sufficient snags to provide for wildlife habitat and other ecological values. • Plant climate-adapted, fire- and drought-resistant trees to achieve desired density, species composition, and spatial pattern.
5) Low density, multi-cohort	• Individual and small group selection harvest every 15–30 years combined with Rx fire. • Maintenance Rx fires between harvests when harvest interval is long (>20 years). • Rx fire or managed wildfire every 10–20 years on sites where the landowner does not have timber revenue objectives.

[a] All silvicultural activities should be designed and implemented with careful consideration of the silvicultural system elements listed in Box 14.1.

14.3.1 Incorporating Prescribed Fire in Silvicultural Treatments

A hallmark of ecologically based forest management is working with, not against, the natural disturbance regime. In this forest type, ecologically based silviculture should integrate prescribed fire with mechanical treatments (Figure 14.6), reflecting the central role of frequent surface fires in driving natural forest development and ecosystem function, and because it is the most effective treatment to manage surface fuels [5] and reduce risk of severe wildfires [11]. Use of prescribed fire in the western United States is often challenging due to operational and social factors. It is nevertheless a science-based goal foresters should strive to attain.

Mechanical harvests alone, even when whole tree yarding is utilized, perpetuate or augment surface fuels. Consequently, wildfires in units treated with mechanical methods alone often burn at higher severity compared to sites treated with a combination of harvest and prescribed fire or prescribed fire alone [11]. There are of course costs, as well as risks, associated with using prescribed fire. But forgoing those risks in the short term only increases the risk of severe wildfires in the future. When prescribed fire is not feasible, alternatives such as pile burning and mastication can be used to reduce surface fuels, but they are less effective at reducing fire intensity, facilitating tree regeneration, cycling nutrients, and restoring understory plant communities.

14.4 Example Applications of Ecological Silviculture in Contrasting Initial Conditions

Five structural conditions illustrate the spectrum of current conditions in ponderosa pine and dry mixed-conifer ecosystems (Table 14.2). Conditions 1–3 are characterized by elevated risk of high-severity wildfire and low resilience to stressors like drought and bark beetles. Treatments in these initial conditions prioritize risk reduction in the short term, a prerequisite for sustainable long-term management. Condition 4 addresses the increasingly common problem of how to manage after an uncharacteristically severe wildfire. Condition 5 represents the target condition for frequent fire forests – low-density, fine-grained mosaic structure dominated by large, fire-resistant trees. While these five examples do not capture every condition that exists, the forester can use them to tailor treatments to their specific situation. In all the scenarios described below, a follow-up surface fuel treatment – ideally with prescribed fire (Figure 14.6) – should be used in combination with harvest or noncommercial thinning treatments to reduce surface fuels and create regeneration opportunities for shade-intolerant, fire-resistant species (Table 14.1).

14.4.1 High Density, Even-Aged

This condition results from clear-cut or seed tree harvests and subsequent development of a dense, even-age forest either from natural regeneration, planting, or a combination thereof. This condition can also originate from a high-severity fire followed by dense natural regeneration. Old or large legacy trees are often absent or rare.

Prescriptions are designed to reduce stand density, promote large tree development, shift composition to fire- and drought-tolerant species, and regenerate a new cohort of fire-resistant trees in openings. Restoring a fine-grained spatial mosaic is another key objective and explicit prescription targets for clumps and openings are typically necessary to accomplish this [9, 12, 13].

For management units where commercial thinning is possible, average density targets for these treatments generally range from 50 to 150 trees ha^{-1} or about 9–18 m^2 ha^{-1} of basal area (20–30% of max SDI or stocking). In young plantations, noncommercial, variable-density thinning (VDT) can be used. In some cases, two or three thinning entries can be conducted to gradually reduce density toward these levels. This will shift forest development towards a multi-age structure more slowly but produce revenue periodically over time.

14.4.2 High Density, Multi-Cohort with Abundant Fire- and Drought-Tolerant Species

These forests result from infilling of young trees after fire exclusion and selective logging of some portion of the large and old fire-resistant trees. A similar condition can develop 15–30+ years after fuel reduction and restoration treatments or mixed-severity wildfire. Due to high density and abundant surface and ladder fuels, crown fire risk in these stands is typically very high.

Prescriptions of this type have two primary objectives. First is to decrease fire risk and drought stress for the existing large and old fire-tolerant trees. This is accomplished by removing almost all young trees from within 1–2 times the dripline (about 8–15 m) of large and old trees. The second objective is to restore the desired species composition, density, and spatial arrangement of lower cohorts by thinning the understory and midstory trees in the remainder of the stand. Depending on conditions, this can be accomplished through a combination of commercial (Figure 14.7) and noncommercial thinning, or just a noncommercial treatment of the smaller diameter classes, often called *ladder fuel treatments*. Explicit prescription targets for clumps and openings may be necessary to achieve desired spatial variability targets [13].

14.4.3 High-Density Lacking Healthy Trees of the Desired Species

This condition encompasses a range of stand structures with insufficient healthy trees of climate-adapted, fire- and drought-tolerant species to retain in either a commercial or noncommercial thinning treatment. This condition is most common on mixed-conifer sites where the fire-tolerant component was harvested, and where existing trees of any species have been heavily impacted by insects or pathogens. Another example is plantations where inappropriate species or offsite seed stock were used.

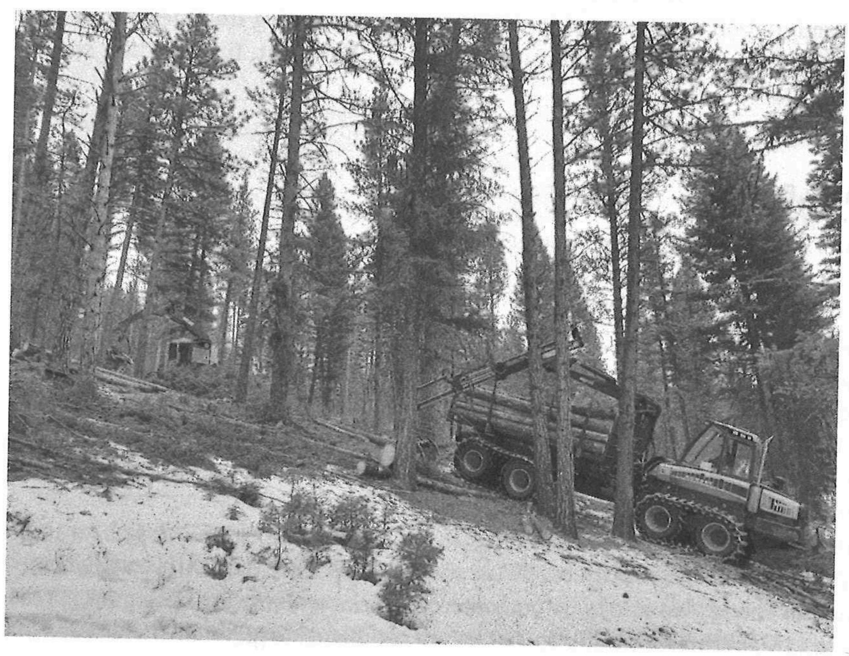


Figure 14.7 Cut-to-length harvester (left) and forwarder (right) system being used to implement an ecological silviculture treatment in a dry mixed-conifer ecosystem, western Montana, USA. *Source:* Andrew J. Larson.

A regeneration treatment is generally necessary to address the primary need to establish a new cohort of trees. The amount and spatial location of retention will be a function of the density of existing fire- and drought-tolerant, healthy trees.

In most cases, planting will be necessary to establish a new cohort of climate-adapted, fire- and drought-tolerant species. Planting at lower densities (e.g. 100–250 trees ha^{-1}) in a variable spatial pattern that takes advantage of variable site conditions can establish a pattern of clumps, individuals, and openings [14] and may improve survival and growth of regeneration. Including planting stock from a seed zone that is better adapted to projected future climates should be considered.

14.4.4 Recent Moderate- or High-Severity Wildfire

Due to the increasing extent of large wildfires in the western United States burning under extreme conditions, many areas in conditions 1, 2, and 3 are experiencing wildfires before an initial restoration treatment is conducted. These fires often result in moderate (25–70%) to high (70–100%) mortality of the overstory trees. Treated stands can also experience high mortality in extreme fire weather conditions, especially where prescribed fire was not conducted. After a fire, foresters can evaluate wildfire effects relative to ecological silviculture goals and then develop postfire silvicultural prescriptions that enhance positive wildfire effects and mitigate negative effects [15].

Moderate-severity fire can accomplish many of the goals of ecological silviculture treatments by reducing tree densities, creating openings and regeneration opportunities, shifting species composition, and consuming surface fuels. Moderate-severity fire produces many snags, however, that lead to abundant surface fuels 5–15 years postfire, increasing risk of future high-severity fire [15, 16]. These fires present an opportunity to "finish the job" by harvesting the trees that would have been removed in an ecologically based green tree treatment (conditions 1–3 above), whether they are alive or dead. Appropriate numbers, sizes, and species of snags can be left for wildlife habitat while treating noncommercial-sized trees and activity fuels. If implemented quickly (ideally the winter after the fire in conditions that protect soils), some revenue can be generated to offset costs and reduce the cost and complexity of future entries.

High-severity fire often sets back development of the desired open canopy, multi-age mosaic structure in this forest type. After a high-severity fire managers must first decide whether to remove a portion of the killed trees. The burned forest retains significant ecological values, including the habitat and carbon values of snags and downed logs. On the other hand, high-severity fire often results in uncharacteristically large amounts of dead wood and fuels that make future prescribed fire challenging [16]. Hence, some removal of fire-generated dead trees may be ecologically justified, and treatments can retain live trees, snags, and dead wood based on ecological needs. These benefits must be weighed against potential negative effects from postfire harvest on soils, aquatic systems, and other resources on a case-by-case basis.

The second postfire management decision is whether to replant [15, 16]. Natural tree regeneration, especially of ponderosa pine, can be limited in large patches of high-severity fire due to seed source limitations and unfavorable environmental conditions in the years following the fire. This may be desirable from a landscape perspective as non-forest patches were historically more common in frequently burned landscapes and have many ecological benefits. The decision to replant depends on whether restoring a forest ecosystem on the affected site makes sense given climate change predictions, landscape context, and the objectives of the landowner [15]. If the answer is yes, then planting may be required to achieve the desired density, spatial pattern, and species composition [14], especially in large high-severity patches.

14.4.5 Low Density, Multi-Cohort

This structural condition is the target for frequent fire forests (Figures 14.2 and 14.3). Treatments in conditions 1–4 are designed to move stands toward this condition class. Multiple cohorts exist across the stand in a range of clump sizes but are generally spatially segregated so that tree clumps with multilayered canopies are rare. Overstory density, canopy cover, and surface fuel levels are low; large and old trees of fire-resistant species comprise most of the basal area (Figure 14.2).

Managers have two options for this condition. The first option is to periodically (5–20-year intervals) utilize prescribed fire or managed wildfire to perpetuate stand development processes and resulting conditions typical of the natural model.

The second option is multi-age management designed with the natural model of forest development as a guide (7 pp201). In this forest type, this means a flexible combination of single tree and small group selection with legacy retention that is ideally coupled with prescribed fire or managed wildfire. The natural model of forest disturbance and development is best approximated by area-based silvicultural methods that seek to maintain a shifting mosaic of small patches (about 0.02–0.5 ha) of different structural conditions across a management unit [17]. For example, 20–40% of the area can be in a mixture of openings with and without clumps of regeneration, 10–20% in patches of saplings, 10–30% in medium trees, and 30–40% large trees [10, 12]. Targets for different sizes of tree clumps, as well as the sizes and numbers of openings, can also be used to guide implementation using the Individuals, Clumps, and Openings approach [9, 13, 18]. Specific targets will depend on stand conditions, recent disturbances, landowner objectives, and other factors, and can vary over different entries.

In this system, commercial removal of trees, noncommercial thinning of smaller trees, prescribed fire or other surface fuel treatments, and regeneration are accomplished as needed during the same entry or within a few years of each other. Across a stand, individual tree selection is used to thin clumps or patches of small and medium-sized trees generally from below, although some larger trees may be removed to achieve species composition or other goals. Over several entries, clump sizes are reduced, leaving larger and more vigorous individual trees, as well as some trees with decadent features important for wildlife habitat (e.g. dead tops, cavities).

In other parts of the stand, small group selection is utilized to harvest a portion of the larger size classes during each entry. This creates new openings, ranging in size from 0.02 to 0.5 ha, where aggregated regeneration of fire- and drought-resistant species is actively promoted, perpetuating a fine-grained structural mosaic. Opening sizes may be larger depending on forest conditions (e.g. root rot pockets), as well as the edaphic and topographic template (e.g., microsites with high or low productivity). Maintaining an old tree population in perpetuity is possible with this system. Decisions about the size and abundance of old tree populations will depend upon the balance between ecological, financial, and other goals for the property.

Following harvest entries with prescribed fire treats activity fuels and creates regeneration sites for the desired tree species. The frequency of entries will depend on site productivity and landowner objectives and will usually range from about 15 to 30 years between harvests. More frequent prescribed fires may be warranted to reduce surface and ladder fuels when the interval between harvests is long (>20 years).

14.5 Climate Change Considerations

The simplest climate change adaptation strategy is to treat dense, fire-excluded sites to reduce stand density and surface fuels, and shift species composition to fire- and drought-resistant species. Frequent fire historically maintained tree density far below carrying capacity [8], providing a substantial buffer against drought and resistance to bark beetle attack. Lower fuel moisture levels due to increasing temperatures and vapor pressure deficits mean increased likelihood of extreme wildfire behavior and effects. Thus, a key climate change adaptation strategy is to utilize prescribed fire or managed wildfire (Figure 14.6) to restore and maintain fuel beds resistant to extreme fire behavior and severe effects. These strategies can maintain forest conditions and buy time to implement other climate adaptation strategies like assisted migration.

Proactive treatments, informed by a landscape strategy [2], to transition moist or cold mixed-conifer ecosystems with mixed-severity fire regimes toward conditions conducive to frequent low-severity fire may be desirable to maintain larger landscape connectivity and ecosystem function.

14.6 Summary

An ecologically based silvicultural system for ponderosa pine and dry mixed-conifer ecosystems involves using active management to create and maintain structural conditions that are very different from an agriculturally based timber production system. Key features of this system that follow from the disturbance regime and natural forest development model include:

1) Maintenance of low density, low competition, and open forest conditions for their greater resilience to fire, drought, and bark beetles.
2) Recruitment and perpetuation of large, old trees, and large-diameter snags and logs.
3) Maintenance of low levels of surface and ladder fuels. Prescribed fire is the most effective approach.
4) Regeneration of fire- and drought-resistant tree species in openings using combined harvest and prescribed fire treatments, and planting as needed, to perpetuate a fine-grained, shifting mosaic structure.

References

1 Hessburg, P.F. and Agee, J.K. (2000). An environmental narrative of Inland Northwest United States Forests, 1800-2000. *Forest Ecology and Management* 178: 23–59.

2 Hessburg, P.F., Churchill, D.J., Larson, A.J. et al. (2015). Restoring fire-prone landscapes: seven core principles. *Landscape Ecology* 30: 1805–1835.

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

4 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: 1243–1249.

5 Agee, J.K. and Skinner, C.N. (2005). Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211: 83–96.

6 Franklin, J.F., Spies, T.A., Van Pelt, R. et al. (2002). Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. *Forest Ecology and Management* 155: 399–423.

7 Palik, B.J., D'Amato, A.W., Franklin, J.F., and Johnson, K.N. (2021). *Ecological Silviculture: Foundations and Applications*. Waveland Press.

8 North, M.P., Tompkins, R.E., Bernal, A.A. et al. (2022). Operational resilience in western US frequent-fire forests. *Forest Ecology and Management* 507: 120004.

9 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.
10 Reynolds, R.T., Sanchez Meador, A.J., Youtz, J.A. et al. (2013). Restoring Composition and Structure in Southwestern Frequent-Fire Forests: A Science-Based Framework for Improving Ecosystem Resiliency. USDA Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-310.
11 Cansler, C.A., Kane, V.R., Bartl-Geller, B.N. et al. (2022). Previous wildfires and management treatments moderate subsequent fire severity. *Forest Ecology and Management* 504: 119764.
12 Tuten, M.C., Sánchez Meador, A., and Fulé, P.Z. (2015). Ecological restoration and fine-scale forest structure regulation in southwestern ponderosa pine forests. *Forest Ecology and Management* 348: 57–67.
13 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: 280–292.
14 North, M.P., Stevens, J.T., Greene, D.F. et al. (2019). Tamm Review: reforestation for resilience in dry western US forests. *Forest Ecology and Management* 432: 209–224.
15 Larson, A.J., Jeronimo, S.M.A., Hessburg, P.F. et al. (2022). Tamm Review: Ecological principles to guide post-fire forest landscape management in the Inland Pacific and Northern Rocky Mountain regions. *Forest Ecology and Management* 504: 119680.
16 Stevens, J.T., Haffey, C.M., Coop, J.D. et al. (2021). Tamm Review: Postfire landscape management in frequent-fire conifer forests of the southwestern United States. *Forest Ecology and Management* 502: 119678.
17 Graham, R.T. and Jain, T.B. (2005). Application of free selection in mixed forests of the inland northwestern United States. *Forest Ecology and Management* 209: 131–145.
18 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.