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Ecological lessons from long-term studies in experimental forests: Ponderosa pine silviculture at Pringle Falls Experimental Forest, central Oregon

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ABSTRACT

The United States Department of Agriculture (USDA) Forest Service celebrated the 100th anniversary of its network of experimental forests in 2008. For a century, the network of experimental forests have contributed immensely—both in the US and around the world—to the practical understanding of the environment and to the formation of management approaches and policies that affect our use of forests and the natural resources they contain. Experimental forests provide places for long-term science and management studies in major vegetation types across the 789,140 km^2 of public land administered by the Forest Service. They also provide an incredible wealth of records and knowledge of environmental change in natural and managed forest ecosystems across the United States. Pringle Falls Experimental Forest (Pringle Falls), southwest of Bend, Oregon, is the oldest experimental forest in the Pacific Northwest and is the site of some of the earliest forest management and silviculture research in this region. Research at this site began in 1914, and it was formally established as part of the national network of experimental forests in 1931 as a center for silviculture, forest management, and insect and disease research in ponderosa pine forests east of the Oregon Cascade Range. As part of the celebration of the Centennial Anniversary of the network of experimental forests, it is timely to examine a few of the ecological lessons that have resulted from long-term studies at Pringle Falls. Two different yet interconnected themes are traced: (1) management of existing old-growth ponderosa pine; and (2) management of young or immature ponderosa pine. Examples of ecological lessons, drawn from long-term studies established or followed by James W. Barrett, Matt D. Busse, Patrick H. Cochran, Walter G. Dahms, F. Paul Keen, Ernest L. Kolbe, Edwin L. Mowat, William W. Oliver, Ram Oren, Chester T. Youngberg, and Jianwei Zhang illustrate how work at Pringle Falls has both pursued and influenced societal demands for forest management strategies, and how this trajectory has cycled back to the themes under which the experimental forest was first established. Finally, these two themes are integrated as drivers for new landscape-scale long-term research at Pringle Falls, designed to evaluate the effects of thinning and fuel reduction treatments on multiple, interacting forest stresses of fire, insects, wind, and climate change.

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1. Introduction

The United States Department of Agriculture (USDA) Forest Service is one of the few natural resource management agencies in the world to have a fully integrated research component and organization (Forest Service Research & Development) with a mandate to make available research findings to federal land managers, states, and private forest owners. A unique foundation of Forest Service Research & Development research infrastructure is the network of 81 experimental forests. The general provisions of the Organic Administration Act of 1897 (16 USC 551), the McSweeney-McNary Act of 1928, and the Forest and Rangeland Renewable Resource Research Act of 1978 (16 USC 1643) authorize the Secretary of Agriculture to designate experimental forests. The McSweeney-McNary Act of 1928 was further implemented by Regulation L-20 in 1930, directing the Chief of the Forest Service to define experimental forests as dedicated to and used for research, and to make them permanently available as field laboratories for intensive investigative work and demonstration of results of forest practices. Because experimental forests are dedicated to research and receive special site protection, they have provided a home for much of the long-term research conducted by Forest Service Research & Development and its partners, with many studies designed to last longer than any one scientist's career. As a result, these experimental forests have provided a wealth of knowledge and records of environmental change in natural and managed forest ecosystems across the United States.

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Beginning in 1908 with establishment of the first formal long-term study documenting weather patterns and climate effects on conifer seed production and seedling establishment at Fort Valley Experimental Forest, Arizona, various Chiefs of the Forest Service have designated additions to the network of experimental forests. Most of the oldest experimental forests were established in the 1930s, with only a few additions in the 1980s and 1990s. Additions in the last 5 years, including the Sagehen Experimental Forest in the Tahoe Basin of California, the Héen Latinee Experimental Forest in southeastern Alaska, the Hawaii Experimental Tropical Forest on the island of Hawaii, and the Olympic Experimental State Forest on the Olympic Peninsula in Washington State, bring the total land area within the network to 3687 km^2. These 81 experimental forests range from Caribbean tropical forest to permafrost-underlain Alaskan taiga forests and Pacific Island tropical forest to interior dry desert, with nearly every major forest ecosystem type in the United States and Puerto Rico represented. They provide places for long-term science and management studies in major vegetation types across the 789,140 km^2 of public land administered by the Forest Service. For a century, experimental forests have contributed immensely—both in the US and around the world—to the practical understanding of the environment and to the formation of management approaches and policies that affect our use of forests and the natural resources they contain. In 2008, Forest Service Research & Development celebrated the Centennial Anniversary of the network of experimental forests. This Centennial Anniversary culminated with the special symposium "Ecological lessons from long-term studies in experimental forests" held during the 7th North American Forest Ecology Workshop (Sharik et al., in press).

The oldest experimental forest administered by the Forest Service in the Pacific Northwest and the site of some of the earliest forest management and silviculture research is Pringle Falls Experimental Forest (Pringle Falls) in central Oregon. Pringle Falls was formally established on May 20, 1931 (Isaac and Kolbe, 1931) as a center for silviculture, forest management, and insect and disease research in ponderosa pine (*Pinus ponderosa*) forests east of the Oregon Cascade Range [Plant species nomenclature follows the PLANTS Database (USDA NRCS, 2009)]. Early research objectives at Pringle Falls focused primarily on silvicultural methods for harvesting multi-cohort old-growth ponderosa pine stands and converting these lower value stands to higher value young, fast-growing single-cohort stands. Management direction and research trajectories during this early period of research were driven by a regional interest in protecting forests from insects and fire. Recently, management direction and research trajectories have shifted from an emphasis on single-cohort stands back to multi-cohort stands with an emphasis on developing late-successional and old-growth structure. The legacy of early research that focused on identifying susceptibility to insect-caused mortality in old-growth pine is proving uniquely valuable today.

As part of the celebration of the Centennial Anniversary of the network of experimental forests, it is timely to examine a few of the ecological lessons that have resulted from long-term studies at Pringle Falls Experimental Forest. Two differing yet interconnected themes will be followed: (1) management of existing old-growth ponderosa pine; and (2) management of immature ponderosa pine. Examples of ecological lessons will be drawn from long-term studies established or followed by James W. Barrett, Matt D. Busse, Patrick H. Cochran, Walter G. Dahms, F. Paul Keen, Ernest L. Kolbe, Edwin L. Mowat, William W. Oliver, Ram Oren, Chester T. Youngberg, and Jianwei Zhang to show how work at Pringle Falls has both followed and influenced societal demands for forest management strategies, and how this trajectory has cycled back to the themes under which the experimental forest was first established. Finally, these two themes appear as drivers for implementing new landscape-scale long-term research to evaluate the effects of thinning and fuel reduction treatments on susceptibility of ponderosa pine forests to multiple, interacting stresses such as fire, insects, wind, and climate change.

2. Establishment history

2.1. Regional setting

Early exploration of central Oregon landscapes was conducted by Peter Skene Ogden in 1825, Nathaniel Wyeth in 1834, and John C. Fremont in 1843. The area was bypassed during the 1840–1870s as westward migration along the Oregon Trail occurred 200 km to the north along the Columbia River. Forest resources were largely unknown until the early 1900s when the US Geological Survey conducted several widespread assessments of timber and grazing lands east of the crest of the Cascade Range. Surveyors found extensive stands of pure, open-grown ponderosa pine dominated by scattered large-diameter trees, few if any down logs, and little litter and woody undergrowth, and concluded that fire was the noticeable cause of this unique forest structure (Languille et al., 1903). This broad belt of forest extended east from the lower slopes of the Cascade Range to the high desert fringe, and from the Columbia River south into California, and encompassed nearly 6000 km^2 (Robbins and Wolf, 1994).

Near the turn of the century, two companies were busy acquiring land and setting in motion a series of events that would shape both forest management and research for the next century. The Brooks-Scanlon operation, led by Minnesota lumbermen Dwight F. Brooks and Joe Scanlon, acquired nearly 600 km^2 of forested land near Bend, OR, and also purchased part-ownership of a small sawmill. At the same time, the rival Shevlin-Hixon company (formed from capital of the extensive Shevlin family timberlands in Minnesota and banker Frank P. Hixon from Wisconsin) acquired about 860 km^2 of holdings in Deschutes, Klamath, and Lake Counties in central Oregon. Central Oregon remained the largest territory in the United States without transportation service (Tonsfeldt and Claeyssens, 2004). Completion of the joint Oregon Trunk and Des Chutes railroad into Bend from the north in October 1911, however, along with the Great Northern line south from Bend soon after, provided the means of transporting logs and finished lumber to distant markets that was needed to start large-scale commercial timber operations. In 1916, both Brooks-Scanlon and Shevlin-Hixon opened sawmills opposite each other on the Deschutes River in Bend. By 1924, Shevlin-Hixon was cutting 200 million board feet a year, and the combined lumber capacity of both pine mills was one of the largest in the world (Robbins and Wolf, 1994). The last major lumber operation arrived in central Oregon in 1938; the Gilchrist Lumber Company started in New Hampshire, relocated to Michigan by 1850, to Wisconsin in the 1880s, and then to Mississippi in 1907 before establishing Gilchrist, OR. They eventually acquired over 400 km^2 of timber holdings in Deschutes, Klamath, and Lake Counties (Tonsfeldt and Claeyssens, 2004). Throughout this period, typical logging methods were little more than liquidation of large old-growth ponderosa pines, made possible by a network of rail lines. Little concern was paid to any future stand composition or structure.

Thornton T. Munger, first Director of the Pacific Northwest Forest Experiment Station (now Pacific Northwest Research Station) spent part of his early career on horseback in central Oregon evaluating the apparent lack of ponderosa pine regeneration and the prolific establishment of lodgepole pine (*Pinus contorta*) after disturbance. He attributed the difference in regeneration success to frequent forest fires and advocated an absolute prevention of wildfire (Munger, 1914). By the early 1930s, timber companies in central Oregon were seeking access to timber on the Deschutes National Forest (Joslin, 2007). As more cutting on federal lands occurred, local managers such as Walter J. Perry advocated for sustained-yield operations while fully recognizing that the scientific and economic basis for sustainability remained lacking (Perry and Joslin, 1999). Munger established as a research priority for the newly organized Pacific Northwest Forest Experiment Station the discovery of ecologically and economically viable silvicultural systems for managing ponderosa pine, the most important timber species in the interior Pacific Northwest (Joslin, 2007). He also located a large tract of representative old-growth ponderosa pine along the upper Deschutes River and in 1914 recommended it be set aside for research. This site was to become the Pringle Falls Experimental Forest and research conducted at this site was to aid national forest managers to sustain timber harvests of ponderosa pine on federal lands into the 1990s.

2.2. Establishment of Pringle Falls Experimental Forest

Pringle Falls Experimental Forest lies within the Deschutes National Forest in central Oregon and is about 48 km southwest of Bend, OR (Fig. 1). It is named after a narrow series of cascades on the Deschutes River and a nearby platted town site on land owned by Octavius M. Pringle (McArthur and McArthur, 2003). Pringle Falls exists as two separate but closely spaced units (Pringle Butte and Lookout Mountain). Munger selected the 3043-ha Pringle Butte unit (lat. 43°43′N; long. 121°36′W) in 1914 because it was dominated by old-growth ponderosa pine found throughout the region, was near the Deschutes River, was in federal ownership since establishment of the Deschutes National Forest in 1908, and was near the rapidly expanding network of rail beds used for transporting logs. On May 20, 1931, Forest Service Chief Robert Y. Stuart exercised the authority vested in him by Regulation L-20 to designate as an experimental forest the lands described within an establishment report prepared by Leo A. Isaac and Ernest L. Kolbe. The 1432-ha Lookout Mountain unit (lat. 43°48′N; long. 121°41′W), containing mostly young stands from two stand-replacement fires, was added in 1937 (USDA Forest Service, 1937). Terrain is flat or gently sloping near the perimeter and more steeply sloped near the center of both units. The surrounding landscape is dotted with small volcanic peaks and basaltic cinder cones that extend above ancient lake basin sediments, characteristic of low- and mid-elevation portions of the High Cascades physiographic province. The actual Pringle Butte is a shield volcano some 5 million years old. Elevations extend from 1294 to 1890 m.

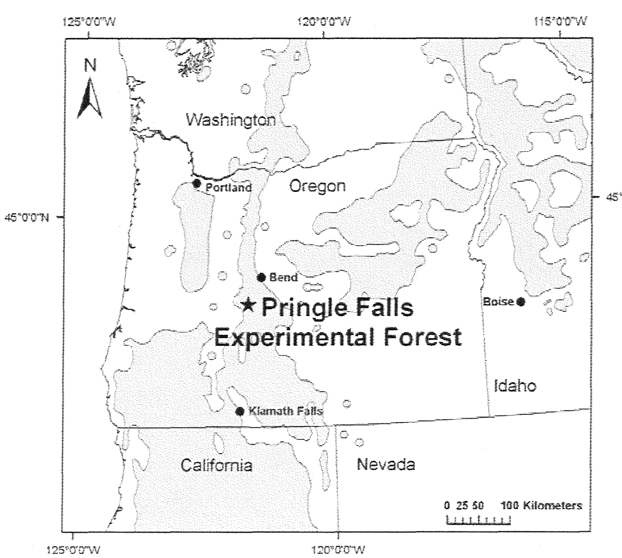

Fig. 1. Pringle Falls Experimental Forest in central Oregon, with distribution of ponderosa pine (*Pinus ponderosa*) depicted by shading.

Soils are well drained, relatively undeveloped loamy coarse sands and ash 80–130 cm in depth, derived from 6600-year-old aerial deposits of dacite pumice and ash after the explosion of ancient Mount Mazama (now Crater Lake). The nearest weather station is about 6 km to the southwest at Wickiup Dam, OR (lat. 43°41′N, long. 121°41′W; 1330 m in elevation) with continuous records since 1941 (Fig. 2). The mean annual temperature at Wickiup Dam is 6.4 °C, and the mean annual precipitation totals 519 mm, mostly as snow during winter or rain during early summer convection storms. Precipitation near the top of Lookout Mountain probably approaches 1000 mm annually. The Deschutes River, a designated Wild and Scenic River because of outstanding scenic and recreation values, flows northeasterly through the Pringle Butte unit. Two parcels within the Pringle Butte unit totaling 470 ha compose a Research Natural Area, established as a designated reserve for non-manipulative research in 1936 in recognition of both old-growth ponderosa pine and lodgepole pine stands (Hall, 1972).

Ponderosa pine is the dominant tree species throughout Pringle Falls, especially at low elevations and on southerly aspects. Flat benches and small slope pockets that collect cold air support the more frost-tolerant lodgepole pine. Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), white fir (*Abies concolor*), sugar pine (*Pinus lambertiana*), western white pine (*Pinus monticola*), and mountain hemlock (*Tsuga mertensiana*) occur at elevations and aspects with increasing moisture availability. Understory plant communities are dominated by shrubs, including antelope bitterbrush (*Purshia tridentata*) on flats at low elevation and snowbrush ceanothus (*Ceanothus velutinus*), greenleaf manzanita (*Arctostaphylos patula*), and giant chinquapin (*Chrysolepis chrysophylla*) on steeper slopes.

Immediately after formal establishment, the first headquarters building was constructed on the bank of the Deschutes River (USDA FS, 1931). Additional office and headquarters infrastructure were constructed on 10 ha in 1933 through the efforts of Civilian Conservation Corps (CCC) personnel under the direction of Kolbe (USDA FS, 1933). Kolbe also oversaw construction of the current administration building by Works Progress Administration (WPA) crews in 1935 and wrote the first comprehensive research plan for the experimental forest. The plan focused on ponderosa pine and included the following three objectives: (1) determine the best

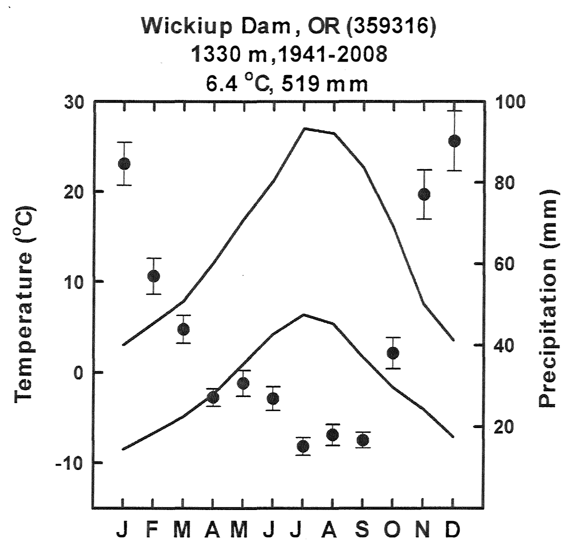

Fig. 2. Climatic features near Pringle Falls Experimental Forest in central Oregon. Pattern of mean monthly maximum temperature and mean monthly minimum temperature (left axis and solid lines), with the pattern of mean monthly precipitation (right axis, dots with standard error bars) for the period of 1941–2008 at Wickiup Dam, OR.

methods of harvesting the virgin ponderosa pine stands for most profitable permanent production; (2) develop methods of thinning, pruning, and other stand improvement in immature stands that are feasible and effective; (3) investigate the effectiveness of various methods of protecting forests against fire and insects (Kolbe, 1938).

3. Lessons from early long-term research

3.1. Management of existing old-growth ponderosa pine

During the 1920s and 1930s, outbreaks of western pine beetle were (*Dendroctonus brevicomis* LeConte) were prevalent throughout the west, and Forest Service timber managers struggled to design and implement timber harvests in ponderosa pine stands in advance of bark beetles. F. Paul Keen, an early research entomologist with the Bureau of Entomology and Plant Quarantine (a former agency of the USDA), monitored tree mortality among nearly 22,000 ponderosa pines in central and southern Oregon and northern California between 1928 and 1931. He later published the first known work originating from Pringle Falls, a rating system the susceptibility of ponderosa pine trees to western pine beetle attack (Keen, 1936, 1943). Keen used tree age, overstory dominance, and tree vigor to describe 16 classes of tree structure and their susceptibility to bark beetle. He recommended the classification as an aid in identifying trees to mark for removal to improve growth in the residual stand and also identifying trees to mark for removal to reduce future mortality. Munger was so impressed with the classification that he adopted it for the Experiment Station and advocated for its use in ponderosa pine management practices and investigations (Munger, 1936). The classification became a standard means of marking ponderosa pine for cutting on national forests, Indian reservations, and other federal lands throughout the Pacific Northwest, Idaho, and California. Keen monitored nearly 4000 additional trees in the later revision that expanded the vigor class definitions. He later documented the age-class distribution in several stands on Pringle Butte, including stands with stems having establishment dates of 1330 A.D. (Keen, 1940). Philip A. Briegleb used trees in Pringle Falls and other sites containing old trees to construct the first set of yield tables with stand growth rates according to Keen's tree classification (Briegleb, 1943).

During the 1930s, costs associated with railroad logging and concerns over bark-beetle outbreaks led to cutting practices that removed 75–85% of the volume of Pacific Northwest old-growth ponderosa pine stands. This level of cutting was recommended by Walter H. Meyer, who began in 1928 to study ponderosa pine growth and yield throughout the Pacific Northwest (Meyer, 1934). While the harvests were generally considered a form of selection cut as part of an uneven-aged selection silvicultural system with a second entry suggested some 40–75 years in the future, Axel J.F. Brandstrom, Senior Economist with the Pacific Northwest Forest Experiment Station regarded the method as essentially a form of clearcutting (Brandstrom, 1937). With the advent of crawler tractor and truck, some silviculturists asked if lighter cutting was economically feasible (Munger and Briegleb, 1942). One of the earliest silvicultural studies to address this question was a test of cutting methods with different intensities of selection, initiated in 1937 along the northeast slope of Pringle Butte (Kolbe and McKay, 1939). Seven plots were established on 205 ha in a solid block of old-growth ponderosa pine. Intensities of cut were 20, 40, 60, and 80% volume removal. For each degree of cut except 80%, two contrasting marking strategies were applied: a "thrift" marking in which the trees of poorest vigor and growth and of highest susceptibility to insect-caused mortality were cut, and a "value" marking in which the trees of high value and low earning power were removed. In both types of marking, trees of highest risk were the first priority for cutting regardless of value, and were removed to salvage what would be lost and to reduce the likelihood of additional mortality from insects. The seventh plot implemented the typical 80% removal. Shevlin-Hixon was awarded the sale and logging began in August, 1937, with CCC enrollees at Pringle Falls marking tree numbers on the ends of each log for identification in a mill-scale study which was to follow after logging was completed (Cowlin, 1988). Thrift marking was later recognized as "maturity selection" and was often compared to improvement selection, a similar approach developed during the same time at Fort Valley Experimental Forest in Arizona (O'Hara, 2005). Mortality after the initial cuttings was assessed by annual 100% tallies, and Mowat (1948, 1961) reported that the thrift (or maturity) marking showed lower losses by insect attack than did the value marking, and the 20% cut was as effective as the heavier cuts in reducing total mortality (Fig. 3). Unfortunately, the design of this study, which lacked replication and controls, prevented a rigorous analysis of treatment effects on residual stand growth (Dahms, 1951) and it was abandoned in the 1960s.

Current amounts of old-growth ponderosa pine in the Pacific Northwest are estimated to range from 3 to 15% of pre-1900 levels (Bolsinger and Waddell, 1993; Perry et al., 1995; Beardsley et al., 1999). The methods-of-cutting study at Pringle Falls was instrumental in shifting the intensity of cutting to lower levels in old-growth ponderosa pine throughout the Pacific Northwest. Because of this study, relatively large blocks of old-growth ponderosa pine remain on and in the vicinity of Pringle Butte;

Fig. 3. Ponderosa pine (*Pinus ponderosa*) stand at Pringle Falls Experimental Forest cut in 1937 under a 40% thrift maturity selection marking. Photo taken in 1951 (14 years after treatment); Edwin L. Mowat in foreground.

Fig. 4. Old-growth ponderosa pine (*Pinus ponderosa*) stand at Pringle Falls Experimental Forest restored to reference conditions. Photo taken in 2008.

some of these old-growth stands were essential in the documentation of repeated cycles of Pandora moth (*Coloradia pandora* Blake) outbreaks during the past 600 years (Speer et al., 2001) and in the description of old-growth reference conditions (Youngblood et al., 2004b). Despite abandonment of the original study, the stands within the methods-of cutting study were not ignored. Continued growth of the dense lodgepole pine understory led to canopy homogeneity, heavy fuel loads, and attendant likelihood of high severity fire. Treatment and monitoring of these stands began in the early 2000s to reduce stand density to old-growth reference conditions, reduce ground fuels, increase the lower crown base height, and protect large old-growth pines (Fig. 4) (Youngblood et al., 2004a). The results from this work emphasized the importance of fire as a key and frequent disturbance factor in this ecosystem.

3.2. Management of immature ponderosa pine

In the late 1950s, practicing silviculturists and researchers began to recognize that the previous four decades of cutting ponderosa pine stands throughout central and southern Oregon resulted in vast areas where natural regeneration had occurred and dense, young single-cohort stands now existed alone or under a partial residual overstory. There was little knowledge to guide the management of these second-growth stands. The Pacific Northwest Forest and Range Experiment Station established a new research emphasis for Pringle Falls that focused on the concept of applied forest management integrated across disciplines of silviculture, mensuration, economics, and fire. Studies were to be conducted in small sample-plots and the results were to be extrapolated to operations of commercial size (Cowlin, 1988). James W. Barrett adopted this approach in 1957 with a study that continues today. His study was designed to answer three questions: (1) Can suppressed ponderosa pine saplings develop into crop trees when released by overstory removal and thinning? (2) How do tree and stand growth rates vary with tree spacing? (3) How does the shrub-dominated undergrowth vegetation influence development of thinned, second-growth stands? The unthinned old-growth ponderosa pine stand in the Pringle Butte unit consisted of large-diameter trees in the overstory (about 50 trees ha^{-1}) and a dense 40- to 70-year-old understory (about 17,300 saplings ha^{-1}) (Barrett, 1960). Saplings averaged about 2.5 cm in diameter and 2.4 m in height before thinning. Undergrowth consisted of mostly antelope bitterbrush, snowbrush ceanothus, greenleaf manzanita, and scattered graminoids. Barrett first designed and implemented an overstory removal cut designed to protect the understory ponderosa pine saplings. His procedures included identification of skid trails before logging, directional falling, and the use of central landings, and his recommendations helped ensure survival of advance regeneration during operational-scale sales, thereby reducing the time to reach rotation age by 20–50 years because fill-in planting was unnecessary (Barrett, 1960).

After overstory removal, 30 rectangular 0.08 ha plots were selected within a 65 ha area. Each 24.1 m × 32.2 m plot was surrounded by a 10 m buffer. Residual ponderosa pine saplings were thinned in 1958 to 2470, 1236, 617, 309, and 154 saplings ha^{-1} (or 2.0, 2.8, 4.0, 5.7, and 8.0 m spacing). All logging and thinning slash was removed from the plots. Undergrowth was removed from three of the six plots of each spacing treatment; on the remaining plots, undergrowth was measured as percent cover by using line-point sampling with 100 points per plot. Initial diameter and height measurements of all residual saplings were recorded in 1959. In 1963, after four growing seasons, saplings at the lower densities had improved crown vigor with longer, larger needles compared to saplings at higher densities (Barrett, 1965). Annual radial increment was 8.5 mm on plots spaced to 154 saplings ha^{-1} and half of that where 2470 saplings ha^{-1} remained. Removal of undergrowth vegetation significantly increased the diameter increment of saplings throughout the range of spacings and was especially pronounced on saplings with wider spacing. Annual height increment of saplings also increased with wider spacing. Average percentage of cover of undergrowth vegetation tended to increase with wider sapling spacing.

Barrett continued to maintain these plots, keeping the undergrowth-free plots clean by hand-pulling shrubs each year (Barrett, 1970, 1973). Through the first 12 years of the study, mean annual diameter increment for saplings on plots with the widest spacing and undergrowth vegetation removed was 14.2 mm and 3.5 mm for saplings on plots with the highest density and undergrowth retained. Mean sapling height was 7.6 m and mean annual height increment was 37 cm during the last four growing seasons on plots with the widest sapling spacing and undergrowth vegetation removed, and mean sapling height was 5.0 m and mean annual height increment was 6 cm during the same period on plots with the highest density of saplings and undergrowth retained. Increased growing space and reduced competition from undergrowth vegetation also resulted in larger branches. Barrett concluded that 10 years of stand growth was saved by removing the shrub competition in the early part of stand development. Thinning also stimulated growth of undergrowth vegetation on plots left undisturbed. Antelope bitterbrush and Ross sedge (*Carex rossii*) were the undergrowth vegetation species most responsive to overstory removal and thinning. After 20 years, low-density plots contained less wood fiber than high-density plots. Saplings in low-density plots, however, were larger and collectively produced nearly as much wood volume annually as did high-density plots (Barrett, 1982). Stand density and undergrowth vegetation had significant effects on height growth. Undergrowth vegetation had the greatest effect on height growth at the lower density, reducing growth from 15 to 50%.

While continuing to monitor sapling growth, Barrett expanded his scope of interest and investigated interrelated lines of ecological responses by involving Oregon State University forest soil scientist Chester T. Youngberg to investigate soils water relations and tree physiologist Ram Oren to explore tree vigor and water use. Soil moisture use was calculated as an indicator of site occupation and thus wood production. Soil moisture was measured beginning 2 years after overstory removal and thinning of residual saplings and continued for three successive growing seasons. Water use increased with sapling density; total amount of water use was 1.6 times greater on plots containing 2470 saplings ha^{-1} than on plots containing 154 saplings ha^{-1}. The most rapid use of soil moisture occurred during midsummer when almost no precipitation occurred (Barrett and Youngberg, 1965). With Oren's help, Barrett showed that stand growth was directly proportional to canopy leaf area (Oren et al., 1987). Leaf area index (square meters of foliage per square meters of ground) was evaluated with sapling height and diameter data collected over 24 years. Growth efficiency of individual saplings was estimated based on growth in stemwood biomass and estimated leaf area. At low leaf area indices, wood production per unit of leaf area was more efficient, particularly in stands where the undergrowth had been removed. Sapling growth efficiency decreased rapidly as the canopy developed. Leaf area index appeared to be approaching maximum at the densest stocking levels. The main effect of undergrowth vegetation removal was expressed at low leaf area indices and was attributed to increased available water in the soil profile. Available water was used more rapidly in stands with low leaf area and undisturbed undergrowth.

The next set of researchers to continue the legacy established by Barrett included microbiologist Matt D. Busse, soil scientist Patrick H. Cochran, and research foresters Jianwei Zhang and William W. Oliver. These researchers not only followed the development of saplings into trees, but used the accumulated data to address questions beyond the scope of the originally conceived study. After 35 years, Busse et al. (1996) concluded that tree growth, as measured by periodic annual increments of basal area, height, and volume, was reduced by competing undergrowth vegetation during the first 12–20 years but not from 21 to 35 years of stand development. Soil C, N, and microbial biomass were quantified by sampling to 24 cm depths during the summer of 1994. Soils in plots where the undergrowth was retained had greater microbial biomass and greater C and N in the O horizon and upper 4–12 cm of mineral soils than plots where the undergrowth was removed. While shrubs in the undergrowth contributed somewhat to N_2 fixation, the greatest increase in N in the O horizon and upper 24 cm of soil was likely either C input from litter and roots, or stabilization of organic matter. Busse et al. (1996) related the differences in soil nutrients to long-term changes in soil quality in the context of fire management in ponderosa pine ecosystems, and suggested that use of prescribed burning to reduce fuels could also reduce overall stand productivity.

Cochran also analyzed growth patterns on the same plots after 35 years. Quadratic mean diameter ranged from 14.7 cm on the highest density plots with undergrowth vegetation present to 36.1 cm on the lowest density plots with undergrowth vegetation removed (Fig. 5). Total tree height ranged from 9.5 m on the highest density plots with undergrowth vegetation present to 16.2 m on the lowest density plots with undergrowth vegetation removed (Fig. 6). After 35 years, the once-spaced saplings had matured into trees that were developing full crown characteristics. Height growth increased linearly and stand cubic volume growth decreased linearly as spacing increased (Cochran and Barrett, 1999). Diameter growth increased nonlinearly with decreasing stand density while stand basal area growth decreased nonlinearly with decreasing stand density. Unlike earlier suggestions alluding to the role of soil quality, growth rates for the largest trees on the plots were shown to have decreased because of competition with smaller trees. Cochran and Barrett (1999) suggested that trees on the more dense plots would soon become susceptible to bark beetles, and that thinning in similar stands of young ponderosa pine should leave at least 4.3 m between remaining trees while wider spacing may be warranted to accelerate the development of mid-seral tree structure.

Zhang and co-workers compared data from 35 years of change in structure at these plots in Pringle Falls with similar plots in ponderosa pine at two sites in California, with Pringle Falls

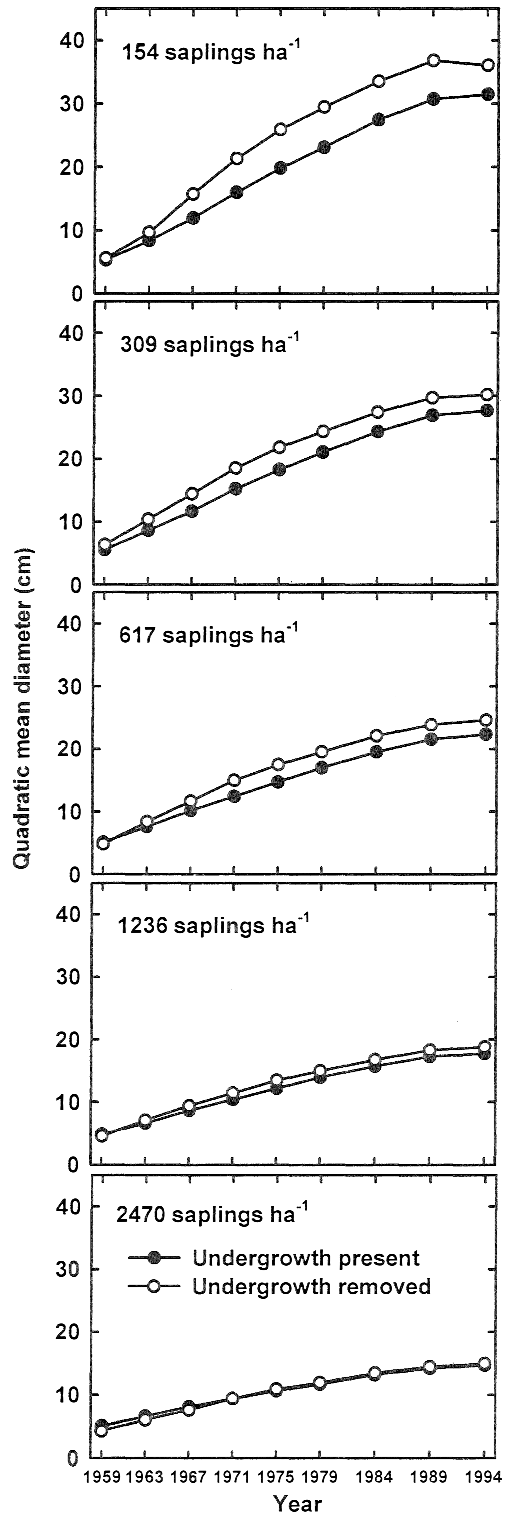

Fig. 5. Changes in quadratic mean diameter (cm) for ponderosa pine (*Pinus ponderosa*) suppressed saplings thinned in 1959 into five density levels and undergrowth either retained (filled circles) or removed (open circles), Pringle Falls Experimental Forest, central Oregon. Source: Cochran and Barrett (1999).

representing a mid-point along a gradient of site productivity (Zhang et al., 2006). They concluded that periodic volume growth declined substantially on the Pringle Falls plots during the 10-year period from 1985 to 1994 similar to that on a higher productivity site in the foothills of the Sierra Nevada in northern California

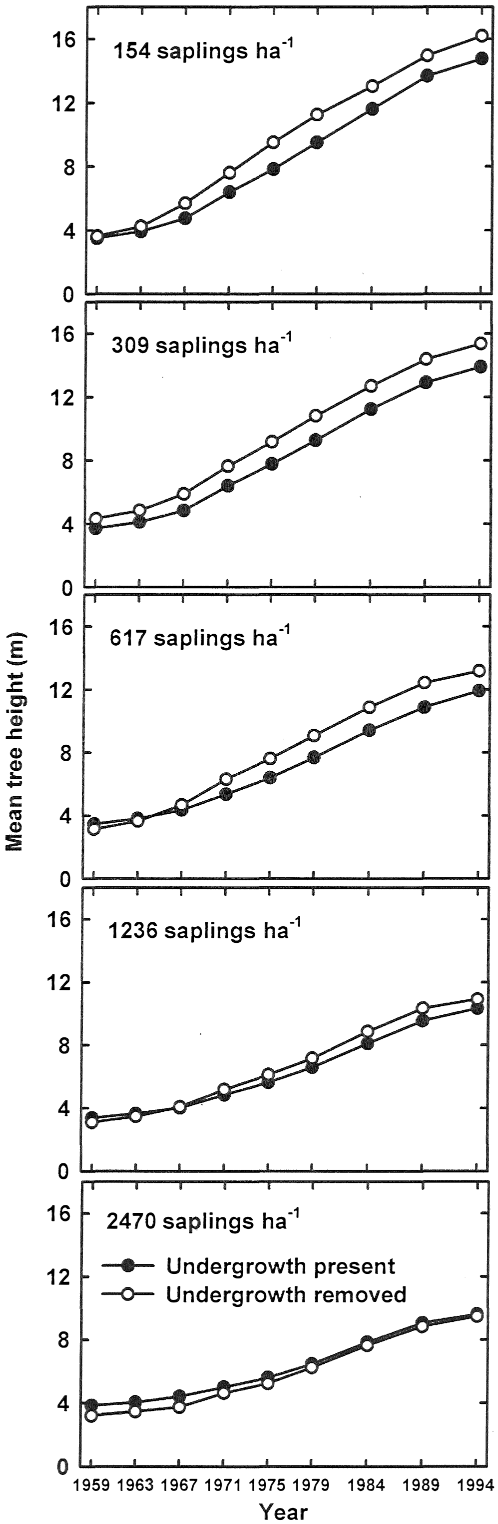

Fig. 6. Changes in mean tree height (m) for ponderosa pine (*Pinus ponderosa*) suppressed saplings thinned in 1959 into five density levels and undergrowth either retained (filled circles) or removed (open circles), Pringle Falls Experimental Forest, central Oregon. Source: Cochran and Barrett (1999).

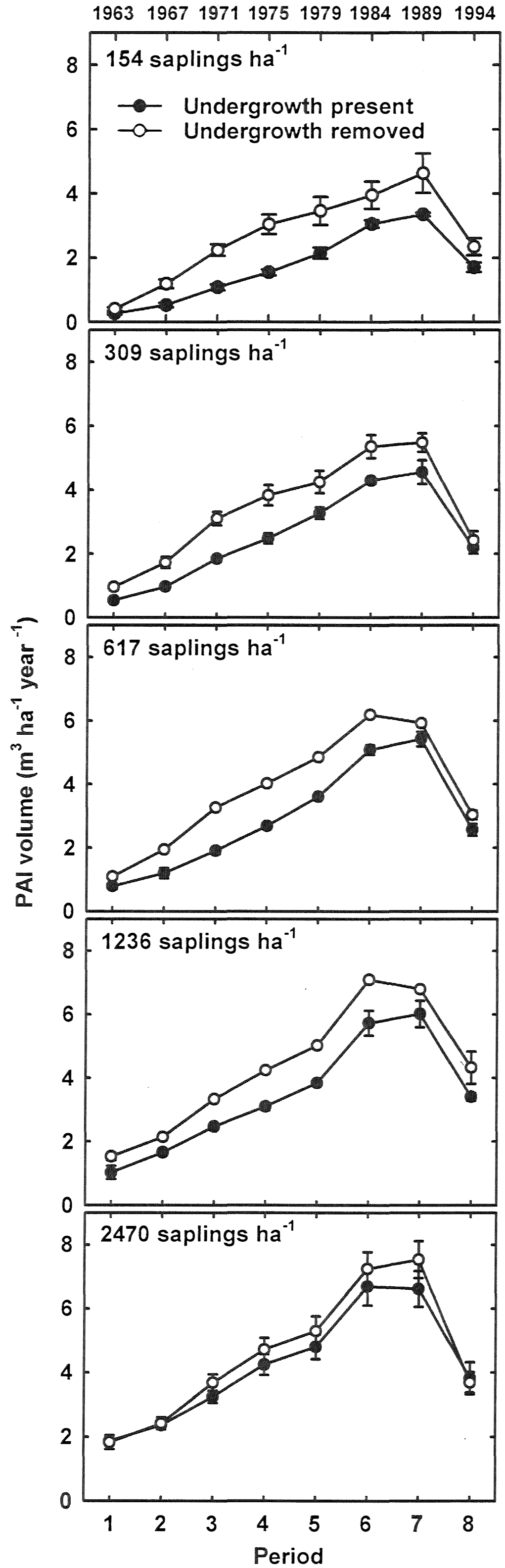

Fig. 7. Changes in periodic annual increment (PAI) of volume ($m^3\ ha^{-1}\ year^{-1}$, mean ± standard error) for ponderosa pine (*Pinus ponderosa*) suppressed seedlings thinned into five density levels and undergrowth either retained or removed, Pringle Falls Experimental Forest, central Oregon. Eight periods correspond to end-of-period years at the top of the graph. Period 1 (1960–1963), 2 (1964–1967), 3 (1968–1971), 4 (1972–1975), 5 (1976–1979), 6 (1980–1984), 7 (1985–1989), 8 (1990–1994). Source: Zhang et al. (2006).

because of confounding effects of mortality, drought, inter-tree competition, and insect defoliation (Fig. 7). Further, tree-shrub competition, evident in earlier periods, was no longer occurring and had likely shifted to tree-tree competition (Zhang et al., 2006).

3.3. Additional studies

The two suites of studies described above, methods-of-cutting in old-growth ponderosa pine and spacing in young ponderosa pine saplings, certainly were not the only long-term research studies at Pringle Falls. A bibliography of research conducted at Pringle Falls listed 119 contributions to the scientific literature published between 1930 and 1993 (Youngblood, 1995); many of these citations summarize studies extending several decades. Other early long-term studies included research on stand structure and growth of suppressed and released ponderosa pine seedlings (Mowat, 1950, 1953), and sanitation and salvage of insect-susceptible ponderosa pine with the objective of fuel and fire hazard reduction (Sowder, 1951). Long-term studies such as these added greatly to management of ponderosa pine throughout forests of the Pacific Northwest at a time when vast segments of these forests were being harvested to meet society's increasing demands for lumber products. Later studies concentrated on determining soil thermal properties, surface temperatures, and seed bed characteristics required for lodgepole and ponderosa pine regeneration from natural seedfall (Dahms and Barrett, 1975); the biology of dwarf mistletoe in ponderosa pine, its spread, and subsequent damage in understory pine (Roth and Barrett, 1985); the effect of underburning on dwarf mistletoe in ponderosa pine (Koonce and Roth, 1980); and the response of ponderosa pine to fertilization (Cochran, 1977). Periodic evaluation of these stands added to an understanding of structural changes occurring in natural and managed stands. In addition, shorter term studies in the Pringle Butte unit addressed the frequency, intensity, and spatial patterns of wildfire in old-growth ponderosa pine stands (Bork, 1984); the relationship between ponderosa pine vigor and mountain pine beetle attacks (Larsson et al., 1983); the effect of fire on root decay in ponderosa pine and the occurrence of fungal microflora on burned and unburned sites (Reaves et al., 1990); and nutritional dynamics of antelope bitterbrush and forage quality for elk and deer after thinning in ponderosa pine and lodgepole pine (Edgerton et al., 1975).

Current long-term research in Pringle Falls is designed to increase our understanding of the processes that regulate or influence the structure, composition, and pattern of forests and that are critical for the maintenance of diverse, healthy, productive, and sustainable forest ecosystems. Specific examples include quantification of stand structure in old-growth ponderosa pine, the role of repeated fire in regulating forest structure and forest health, and the effect of species composition in overall stand production and development.

4. Addressing future management issues with long-term studies at Pringle Falls

Old-growth ponderosa pine forests in the interior Pacific Northwest were fundamentally shaped by frequent low- or mixed-severity wildfires and attacks from insects (Agee, 1993; Fettig et al., 2007) mediated by diverse environmental gradients of topography, soils, and weather. Surface fires controlled regeneration of fire-intolerant species, reduced density of small-diameter stems, consumed litter and down wood, opened stands to increased sunlight, led to vertical separation of fuels by eliminating fuel ladders between the forest floor and the overstory canopy, and maintained relatively stable plant associations. Bark beetles (Coleoptera: Curculionidae, Scolytinae) and wood boring beetles (Coleoptera: Buprestidae, Cerambycidae) attacked and killed trees, and influenced the size, distribution, and abundance of live and dead trees. They targeted at least four types of hosts: large, old, slow growing trees; lower boles and roots exposed after fires; tops of trees weakened by fire; and trees with growth rates slowed by density-dependent competition, drought stress, or other localized disturbances that enabled the beetles to circumvent tree defenses (de Groot and Turgeon, 1998; McCullough et al., 1998; Fettig et al., 2007). Attacks often led to mortality of individual and small groups of trees, created snags, altered the accumulation of fuels and vegetation, and created canopy gaps that provided opportunities for new seedling cohorts. Consequently, the structure of these ponderosa pine forests generally consisted of open, predominantly widely spaced medium to large and old live trees, scattered dead trees, low levels of ground fuels, and continuous low herbaceous understory vegetation (Agee, 1993; Youngblood et al., 2004b; Arabas et al., 2006). Because most of the vast tracts of old-growth ponderosa pine were converted to young stands, the challenge that now faces resource managers is how to integrate knowledge of these same disturbances or their potential surrogates, coupled with poorly defined shifts in regional climate, to better understand how these various agents determine forest structure and composition in young and maturing stands.

Today, many young and maturing ponderosa pine forests have characteristics that place them at greater risk of uncharacteristic severe disturbances. These features include an accumulated mass of down woody debris and continuity of the fuels mosaic at landscape scales, more small trees and fewer large trees, greater amounts of young multi-storied forests with fire-intolerant conifers in both understory and overstory strata, increased fuel ladders that contribute to greater flame lengths during fires, and new or altered forcing of regional climate on plant community structure and organization (Agee, 1993; Harrod et al., 1999; Youngblood et al., 2004b, 2006; McKenney et al., 2007). Increases in overall stand density over the past century have led to increased competition among trees for below-ground nutrients, water, and growing space. Increased competition among trees and reduced tree vigor increases susceptibility to attack from bark beetles and other forest insects and diseases (Fettig et al., 2007). Changes in structure and processes have occurred more recently against a backdrop of climate change and may first be manifest in the distribution of herbaceous species and woody shrubs, and may eventually result in a redistribution of tree species (McKenney et al., 2007; Richardson et al., 2007). Collectively, these altered structural conditions contribute to increased probability of multiple, interacting stresses and may lead to altered or new disturbance regimes that may have both economic and ecological consequences.

Recent presidential initiatives such as the National Fire Plan, the 10-year Comprehensive Strategy, and the Healthy Forests Initiative, and legislation such as the Healthy Forests Restoration Act of 2003 (P.L. 108–148), have promoted the consideration of large scale and strategically located fuel reduction and restoration projects to manage landscapes within the context of ecological processes (USDI and USDA, 2006). These fuel reduction and restoration treatments often are applied in ponderosa pine forests as thinning or prescribed burning projects and are designed to reduce surface fuels, decrease crown density while retaining large live and dead trees of fire resistant species, increase the height to the live crown, and promote late-seral structures, with the goal of reducing the risk of unnaturally severe surface and crown fires (Brown et al., 2004; Agee and Skinner, 2005). Yet there remains uncertainty over the ecological consequences of these treatments. With widespread recognition by scientists and policy makers that climate change is occurring, management options are needed that recognize and accommodate uncertainty in the manifestation of climate change and the interaction of shifting regional climates with vegetation manipulations.

To address these knowledge gaps, a large scale, long-term study is being initiated on about 1413 ha the Lookout Mountain unit at Pringle Falls. This relatively large block of closed-canopy forest has undergone little major disturbance, other than fire exclusion, since about 1845 when a single stand-replacement fire resulted in the establishment of dense ponderosa pine at lower elevations and mixed conifer at higher elevations. These closed-canopy stands have grown exceptionally well, and may represent some of the most productive ponderosa pine sites in central Oregon. Recently, trees have declined in radial growth. Stand density, average diameter, and availability of host species and fuel contribute to a high risk of major disturbance from multiple threats. There is an increasing probability that ponderosa pine stands will support a landscape-scale western pine beetle or mountain pine beetle outbreak, or a large stand-replacing fire event. Five different silvicultural treatments will be applied across 20 large treatment units blocked by elevation and aspect, and the residual stands evaluated for resiliency to multiple, interacting forest stresses of fire, insects, wind, and climate change. Treatments include three levels of density reduction with the lowest about 35% of existing density, one partial overstory removal designed to encourage establishment of a new seedling cohort, and an untreated control.

Six specific research questions or objectives were developed that require different lengths of monitoring and observation. These questions, arranged here from the nearest term to the longest term, include the following: (1) How does the residual stand structure resulting from a set of fuel reduction treatments interact locally with wind to cause additional structural changes? (2) How does the dominant shrub, giant chinquapin (*C. chrysophylla*), respond to a set of fuel reduction treatments? (3) What set of fuel reduction treatments best accelerates the development of large trees while reintroducing natural disturbance processes that provide greater ecosystem resiliency? (4) What is the long-term influence of climate change interacting with a set of fuel reduction treatments on vegetation dynamics and forest structure? (5) Can single-cohort stands be readily converted to multi-cohort stands? (6) Do multi-cohort stands share the same risks of multiple, interacting stresses as single-cohort stands?

The first question is designed to evaluate the long-term susceptibility of stands managed under thinning and fuel reduction regimes to windthrow. Models of disturbances for eastside forest have not incorporated wind as a common event, yet it has long been known that wind affects forest structure. Windspeed may increase in mountainous areas, and prevailing winds are usually greater when winds confront large objects such as isolated mountains. Management practices such as thinning and underburning may contribute to wind damage because individual trees are made more susceptible as stands are opened, the roughness factor is increased, and trees that were in the interior of closed stands become more exposed. In addition, rooting systems may be affected by mechanical equipment or fire. Lookout Mountain provided a unique opportunity to evaluate the effects of wind after thinning and fuel reduction because the site is on an exposed volcanic cone with little surface topography other than elevation and aspect. The working hypothesis is that windthrow and stem breakage in residual trees from wind initially will increase with increasing levels of density reduction. In addition, windthrow and stem breakage may vary with elevation and aspect. This work will provide managers new information on the interaction of disturbance processes that affect forest structure, and provide information on management options that best incorporate wind as a disturbance process.

The second question deals specifically with the response of the dominant shrub, giant chinquapin (*C. chrysophylla*), to thinning and fuel reduction treatments. Giant chinquapin is a native, broad-leaved, sclerophyllous evergreen. In the central Oregon portion of its distribution, it is a long-lived, moderately shade-tolerant arborescent shrub or small tree up to 5 m tall. It regenerates both sexually and vegetatively. Seedling reproduction is generally restricted to mesic sites, while vegetative regeneration is more prevalent on increasingly xeric sites. Thin bark provides little insulation from radiant heat, so fires usually kill the cambium around the base of the stem and lead to sprouting from adventitious buds located on stumps or dormant buds located on an underground burl. Sprouting vigor can be greatly reduced with repeated fire (Martin, 1982). Little is known of how this species contributes to fuel loading and fire behavior in underburns after various levels of thinning, how it may respond to mowing, and how it may respond to climate change. The working hypothesis is that disturbances that are surrogates for low severity wildfires, such as thinning, mowing, and underburning, will stimulate resprouting and climate change will drive giant chinquapin upslope and to more mesic environments. Like the fourth question, this work will provide insights into the effects of climate change, but focuses on a specific shrub species of interest.

The third research question deals specifically with structural changes, especially the restoration of radial growth rates leading to larger tree diameters, while reintroducing surrogates for low and mixed-severity disturbance events. In the context of this study, the combination of thinning, mowing, and underburning are considered surrogates for low and mixed-severity disturbance events. The combination of thinning and underburning may be more effective in reducing fuels and changing diameter distributions, but may produce more varied results that depend, in part, on the amount of fuels added during the thinning activity (Youngblood et al., 2008). Cochran and Barrett's (1999) work with ponderosa pine saplings demonstrated that young ponderosa pine stands respond positively to density reduction. Because mean annual basal area growth is directly related to density, the working hypothesis is that treatments that remove greater levels of tree density eventually result in greater quadratic mean diameter, or more simply, removing more small trees should allow the residual trees to grow to larger diameters. While this hypothesis is known to hold true for young, pole-size stands of ponderosa pine, it is not known if it holds equally true for stands of larger trees when thinning treatments are combined with mowing and underburning. If so, it provides managers additional justification to consider restoration treatments options across a wider array of stand types.

The fourth research question introduces climate change as an additional form of disturbance that has not been adequately addressed in thinning and fuel reduction research. This portion of central Oregon has gone through at least five distinct periods of warming climate over the past 110 years (NASA, 2009). In the Western United States and at the continental scale (1 km), long-term satellite data show consistently earlier onsets of spring greening and corresponding increases in length of growing season (USDA Forest Service, 2009). Small changes in growing season duration may result in expansion of species that have relatively narrow habitat requirements. Lookout Mountain provides a unique opportunity to explore vegetation dynamics under a changing climate regime because it is topographically simplistic, it contains essentially uniform or homogenous soils, and it contains several relatively clear and distinct ecotones in easily recognized plant assemblages. Early indications of vegetation dynamics may become first apparent in the shrub and herbaceous strata with expansion of species from drier sites into those areas that are currently moister as conditions become increasingly stressed. For example, antelope bitterbrush may expand upward in elevation under increasing moisture stress. Understanding these dynamics will provide insights into the effects of climate change at the community scale, and provide managers much needed information on any restructuring of plant composition as a result of regional climate interacting with legacies of past management.

The fifth question is one that has plagued ponderosa pine silviculturists for decades. Remaining interior Pacific Northwest old-growth ponderosa pine forests are predominantly multi-cohort with sometimes ten distinct cohorts in the overstory (Youngblood et al., 2004b). Past management, however, has converted most of the multi- cohort stands to young, single-cohort stands, and much of the ponderosa pine resource is now managed under an even-aged system. Most of our knowledge base for managing ponderosa pine ecosystems is derived from studies conducted in even-aged stands. An uneven-aged management regime that maintains multi-cohort stands is often recognized as advantageous for management of ponderosa pine because of productivity, aesthetics, value for wildlife, and its ease in restoring pre-settlement stand structures (O'Hara, 2005). Few if any empirical comparisons of even-aged and uneven-aged systems exist across any suite of treatments. A fundamental question is how to convert single-cohort stands that are a legacy of past management to multi-cohort stands that may more closely resemble those that developed under pre-Euro-American conditions. This work will provide managers much needed information into the process of restructuring single-cohort stand to multi-cohort stands.

The final question, requiring the greatest time, deals specifically with risks from multiple, interacting stresses. This question addresses the hypothesis that structural characteristics in multi-cohort stands may provide greater resiliency to low and mixed-severity disturbances compared to the structural characteristics in single-cohort stands. We know little about how fire, insects, and climate change will continue to serve as drivers of structural change in multi-cohort stands when compared to single-cohort stands within the same ecosystem. The working hypothesis is that climate change, insects, and perhaps fire will interact to increase tree mortality in relation to relative tree density, density management will delay large tree mortality, and ultimately conversion to multi-cohort structure will provide the greatest degree of resiliency to the interaction of climate change, insects, and fire. This work will provide insights into the effects of climate change at the community scale and provide managers much needed information on the restructuring of forest stands as a result of interacting disturbance regimes and management options to better incorporate these interactions.

5. Summary

Early research objectives at Pringle Falls focused primarily on silvicultural methods for harvesting multi-cohort old-growth ponderosa pine stands and converting these lower value stands to higher value young, fast-growing stands. Management direction and research trajectories during this period were driven by a regional interest in protecting forests from insects and fire. As the economy expanded, the demand for large-diameter logs to feed large and competing ponderosa pine mills grew beyond the regional supply, and research shifted toward more integrative work that encompassed silvicultural methods for managing young single-cohort stands, insect and disease biology, and incorporating sanitation and salvage of ponderosa pine considered highly susceptible to insect attack with fuel and fire hazard reduction. Contributions such as these added greatly to management of ponderosa pine forests throughout the interior Pacific Northwest when vast segments of these forests were being harvested after World War II to meet the nation's increasing demands for lumber products. These early objectives evolved over time to what became a mission statement in 1954 that is still relevant today: *"The mission of the Pringle Falls Experimental Forest is to supply facts, through research, that will aid in the management of both public and private forest resources. More specifically, the objective is to learn the silvicultural and ecological facts about central Oregon's forests and to develop and demonstrate better methods for protecting, harvesting, reproducing and managing them for optimum sustained ecological function and societal value.* Current long-term research in Pringle Falls Experimental Forest is designed to increase our understanding of the processes that regulate or influence the structure, composition, and pattern of forests and that are critical for the maintenance of diverse, healthy, productive, and sustainable forest ecosystems. Current and planned long-term research at Pringle Falls Experimental Forest is important for continued understanding of the dynamics of managed and unmanaged interior Pacific Northwest forests. These studies are essential in providing a baseline for assessing different management strategies for commodity and amenity values, the effects of changing climates on disturbance agents and stand dynamics, and interactions of overstory and understory vegetation. While research goals at Pringle Falls emphasize current priorities of the Pacific Northwest Research Station, Pringle Falls belongs to the national network of experimental forests. It serves as a key component of Forest Service Research & Development and provides a designated land base where innovative approaches to management can be tested and where increased understanding of forest processes can be acquired. Researchers wishing to use Pringle Falls for either manipulative or non-manipulative studies are encouraged to contact the author or the Pacific Northwest Research Station.

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References

Agee, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, D.C., USA, 493 pp.
Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manag. 211, 83–96.
Arabas, K.B., Hadley, K.S., Larson, E.R., 2006. Fire history of a naturally fragmented landscape in central Oregon. Can. J. For. Res. 36, 1108–1120.
Barrett, J.W., 1960. Intensive control in logging ponderosa pine. Iowa State J. Sci. 34, 603–608.
Barrett, J.W., 1965. Spacing and understory vegetation affect growth of ponderosa pine saplings. In: USDA For. Serv. Res. Note PNW-27, Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 8 pp.
Barrett, J.W., 1970. Ponderosa pine saplings respond to control of spacing and understory vegetation. In: USDA For. Serv. Res. Pap. PNW-106, Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 16 pp.
Barrett, J.W., 1973. Latest results from the Pringle Falls ponderosa pine spacing study. In: USDA For. Serv. Res. Note PNW-29, Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 22 pp.
Barrett, J.W., 1982. Twenty-year growth of ponderosa pine saplings thinned to five spacings in central Oregon. In: USDA For. Serv. Res. Pap. PNW-301, Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 18 pp.
Barrett, J.W., Youngberg, C.T., 1965. Effect of tree spacing and understory vegetation on water use in pumice soil. Soil Sci. Soc. Am. Proc. 29, 472–475.
Beardsley, D., Bolsinger, C., Warbington, R., 1999. Old-growth forests in the Sierra Nevada: by type in 1945 and 1993 and ownership in 1993. In: USDA For. Serv. Res. Pap. PNW-RP-516, Pac. Northwest Res. Stn., Portland, OR, USA, 46 pp.
Bolsinger, C.L., Waddell, K.L., 1993. Area of old-growth forests in California, Oegon, and Washington. In: USDA For. Serv. Res. Bull. PNW-RB-107, Pac.Northwest Res. Stn., Portland, OR, USA, 26 pp.
Bork, J.L., 1984. Fire history in three vegetation types on the eastern side of the Oregon Cascades. Ph.D. Thesis. Oregon State University, Corvallis, OR, USA, 94 pp.
Brandstrom, A.J.F., 1937. The role of selection cutting in promoting sustained yield with special reference to ponderosa pine. J. Forestry 35, 142–147.
Briegleb, P.A., 1943. Growth of ponderosa pine by Keen tree class. In: USDA For. Serv. Res. Notes 32, Pac. Northwest For. Exp. Stn., Portland, OR, USA, 15 pp.
Brown, R.T., Agee, J.K., Franklin, J.F., 2004. Forest restoration and fire: principles in the context of place. Conserv. Biol. 18, 903–912.
Busse, M.D., Cochran, P.H., Barrett, J.W., 1996. Changes in ponderosa pine site productivity following removal of understory vegetation. Soil Sci. Soc. Am. J. 60, 1614–1621.
Cochran, P.H., 1977. Response of ponderosa pine 8 years after fertilization. In: USDA For. Serv. Res. Note PNW-301, Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 7 pp.
Cochran, P.H., Barrett, J.W., 1999. Thirty-five-year growth of ponderosa pine saplings in response to thinning and understory removal. In: USDA For. Serv. Res. Pap. PNW-RP-512, Pac. Northwest Res. Stn., Portland, OR, USA, 28 pp.
Cowlin, R.W., 1988. Federal forest research in the Pacific Northwest: the Pacific Northwest Research Station. Olympia Forestry Sciences Laboratory, Olympia,

WA, USA (http://www.fs.fed.us/pnw/olympia/silv/look-back/cowlin1988pnw_history.pdf, 10 Sept. 2009).
Dahms, W.G., 1951. Intensity of cut as related to ponderosa pine management—a statistical approach to the problem of isolating cutting effect. MS Thesis. State University of New York, Syracuse, NY, USA, 116 pp.
Dahms, W.G., Barrett, J.W., 1975. Seed production of central Oregon ponderosa and lodgepole pines. In: USDA For. Serv. Res. Pap. PNW-191, Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 13 pp.
de Groot, P., Turgeon, J.J., 1998. Insect-pine interactions. In: Richardson, D.M. (Ed.), Ecology and Biogeography of Pinus. Cambridge University Press, Cambridge, UK, pp. 354–380.
Edgerton, P.J., McConnell, B.R., Justin, G., 1975. Initial response of bitterbrush to disturbance by logging and slash disposal in a lodgepole pine forest. J. Range Manag. 28, 112–114.
Fettig, C.J., Klepzig, K.D., Billings, R.F., Munson, A.S., Nebeker, T.E., Negrón, J.F., Nowak, J.T., 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle outbreaks in coniferous forests of the western and southern United States. For. Ecol. Manag. 238, 24–53.
Harrod, R.J., McRae, B.H., Hartl, W.E., 1999. Historical stand reconstruction in ponderosa pine forests to guide silvicultural prescriptions. For. Ecol. Manag. 114, 433–446.
Hall, F.C., 1972. Pringle Falls research natural area. In: Franklin, J.F., Hall, E.C., Dyrness, C.T., Maser, C. (Eds.), Federal Research Natural Areas in Oregon and Washington—A Guidebook for Scientists and Educators. USDA For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, pp. PR-1–PR-11.
Isaac, L.A., Kolbe, E.L., 1931. The proposed Pringle Falls Experimental Forest. USDA For. Serv. Pac. Northwest For. Exp. Stn. On file: USDA For. Serv. Pac. Northwest Res. Stn., LaGrande, OR, USA.
Joslin, L., 2007. Ponderosa promise: a history of U.S. Forest research in central Oregon. In: USDA For. Serv. Gen. Tech. Rep. PNW-GTR-711, Pac. Northwest Res. Stn., Portland, OR, USA, 121 pp.
Keen, F.P., 1936. Relative susceptibility of ponderosa pine to bark-beetle attack. J. Forestry 34, 919–927.
Keen, F.P., 1940. Longevity of ponderosa pine. J. Forestry 38, 597–598.
Keen, F.P., 1943. Ponderosa pine tree classes redefined. J. Forestry 41, 249–253.
Kolbe, E.L., 1938. A guide to the Pringle Falls Experimental Forest. USDA For. Serv. Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 18 pp.
Kolbe, E.L., McKay, D.F., 1939. Seven methods of cutting tested at Pringle Falls. In: USDA For. Serv. Res. Notes 27, Pac. Northwest For. Exp. Stn., Portland, OR, USA, p. 1.
Koonce, A.L., Roth, L.F., 1980. The effects of prescribed burning on dwarf mistletoe in ponderosa pine. In: Martin, R.E., Edmonds, R.L., Fulkner, D.A. (and others) (Eds.), Proceedings, 6th Conference on Fire and Forest Meteorology, Seattle, WA, USA, 22–24 April 1980. Society of American Foresters, Bethesda, MD, USA, pp. 197–203.
Languille, H.D., Plummer, F.G., Dobwell, A., Rixon, T.F., Leiberg, J.B., 1903. Forest conditions in the Cascade Range forest reserve—Oregon. USDI, Geological Survey, Professional Paper 9, Series H., Forestry, vol. 6, Washington, DC, USA, 298 pp.
Larsson, S., Oren, R., Waring, R.H., Barrett, J.W., 1983. Attacks of mountain pine beetle as related to tree vigor of ponderosa pine. Forest Sci. 29, 395–402.
Martin, R.E., 1982. Shrub control by burning before timber harvest. In: Baumgartner, D.M. (Comp), Proceedings of the Symposium on Site Preparation and Fuels Management on Steep Terrain, Spokane, WA, USA, 15–17 February 1982. Washington State University, Pullman, WA, USA, pp. 35–40.
McArthur, L.A., McArthur, L.L., 2003. Oregon Geographical Names. Oregon Historical Society Press, Portland, OR, USA, 1073 pp.
McCullough, D.G., Werner, R.A., Neumann, D., 1998. Fire and insects in northern and boreal forest ecosystems. Ann. Rev. Entomol. 43, 107–127.
McKenney, D.W., Pedlar, J.H., Lawrence, K., Campbell, K., Hutchinson, M.F., 2007. Potential impacts of climate change on the distribution of North American trees. BioSci. 57, 939–948.
Meyer, W.H., 1934. Growth in selectively cut ponderosa pine forests of the Pacific Northwest. In: USDA Technical Bulletin No. 407, U.S. Department of Agriculture, Washington, DC, USA, 68 pp.
Mowat, E.L., 1948. Selection cutting reduces ponderosa pine losses at Pringle Falls. In: USDA For. Serv. Res. Note 45, Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 3 pp.
Mowat, E.L., 1950. Cutting lodgepole pine overstory releases ponderosa pine reproduction. J. Forestry 48, 679–680.
Mowat, E.L., 1953. Thinning ponderosa pine in the Pacific Northwest—a summary of present information. In: USDA For. Serv. Res. Pap. 4, Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 24 pp.
Mowat, E.L., 1961. Growth after partial cutting of ponderosa pine on permanent sample plots in eastern Oregon. In: USDA For. Serv. Res. Pap. 44, Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 23 pp. (plus 28 pp. supplement).
Munger, T.T., 1914. Replacement of yellow pine by lodgepole pine on the pumice soils of central Oregon. Proc. Soc. Am. Foresters 9, 396–406.
Munger, T.T., 1936. Report of the Pacific Northwest Forest Experiment Station for the Calendar Year 1936. Pac. Northwest For. Exp. Stn., Portland, OR, USA, 45 pp.
Munger, T.T., Briegleb, P.A., 1942. Recent developments in pine silviculture. Northwest Sci. 16, 40–45.
NASA, 2009. Global Climate Change (http://climate.jpl.nasa.gov, 10 Sept. 2009). National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.
O'Hara, K.L., 2005. Multiaged silviculture of ponderosa pine. In: Ritchie, M.W., Maguire, D.A., Youngblood, A. (Eds.), Proceedings of the Symposium on Ponderosa Pine: Issues, Trends, and Management, Klamath Falls, OR, USA, 18–21 Oct. 2004. USDA For. Serv. Gen. Tech. Rep. PSW-GTR-198. Pac. Southwest Res. Stn., Albany, CA, pp. 59–70.
Oren, R., Waring, R.H., Stafford, S.G., Barrett, J.W., 1987. Twenty-four years of ponderosa pine growth in relation to canopy leaf area and understory competition. Forest Sci. 33, 538–547.
Perry, D.A., Henjum, M.G., Karr, J.R., Bottom, D.L., Bednarz, J.C., Wright, S.G., Beckwitt, S.A., Beckwitt, E., 1995. Interim protection for late-successional forests, fisheries, and watersheds: a summary of the report of the eastside forests scientific society panel. In: Everett, R.L., Baumgartner, D.M. (Comps.), Proceedings of the Ecosystem Management in Western Interior Forests, Spokane, WA, 3–5 May 1994. Department of Natural Resource Sciences, Washington State University, Pullman, WA, USA, pp. 103–114.
Perry, W.J., Joslin, L. (Eds.), 1999. Walt Perry: An Early-Day Forest Ranger in New Mexico and Oregon. Wilderness Associates, Bend, OR, USA, 184 pp.
Reaves, J.L., Shaw III, C.G., Mayfield, J.E., 1990. The effects of *Trichoderma* spp. isolated from burned and non-burned forest soils on the growth and development of *Armillaria ostoyae* in culture. Northwest Sci. 64, 39–44.
Richardson, D.M., Rundel, P.W., Jackson, S.T., Teskey, R.O., Aronson, J., Bytnerowicz, A., Wingfield, M.J., Proches, S., 2007. Human impacts in pine forests: past, present, and future. Ann. Rev. Ecol. Evol. Syst. 38, 275–297.
Robbins, W.G., Wolf, D.W., 1994. Landscape and the intermontane northwest: an environmental history. In: USDA For. Serv. Gen. Tech. Rep. PNW-GTR-319, Pac. Northwest Res. Stn., Portland, OR, USA, 32 pp.
Roth, L.F., Barrett, J.W., 1985. Response of dwarf mistletoe-infested ponderosa pine to thinning: 2. Dwarf mistletoe propagation. In: USDA For. Serv. Res. Pap. PNW-331, Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 20 pp.
Sharik, T.L., Adair W., Battaglia, M., Baker F.A., Comfort, E.J., D'Amato, A., Delong, C., DeRose, J., Ducey, M.J., Harmon, M., Levy, L., Logan, J.A., O'Brien, J., Palik, B.J., Roberts, S.D., Rogers, P.C., Shinneman, D.J., Spies, T., Taylor, S.L., Woodall, C., Youngblood, A, in press. 7th North American Forest Ecology Workshop: Overview. Int. J. Forestry Res.
Sowder, J.E., 1951. A sanitation-salvage cutting in ponderosa pine at the Pringle Falls Experimental Forest. In: USDA For. Serv. Res. Pap. 2, Pac. Northwest For. Range Exp. Stn., Portland, OR, USA, 24 pp.
Speer, J.H., Swetnam, T.W., Wickman, B.E., Youngblood, A., 2001. Changes in pandora moth outbreak dynamics during the past 622 years. Ecology 82, 679–697.
Tonsfeldt, W., Claeyssens, P.G., 2004. Central Oregon: adaptation and compromise in an arid landscape. Oregon History Project, Oregon Historical Society, Portland, OR, USA (http://ohs.org/education/oregonhistory/narratives, 10 Sept. 2009).
USDA Forest Service, 1931. Report of the Pacific Northwest Forest Experiment Station for the Month of August. On file: USDA For. Serv. Pac. Northwest Res. Stn., Portland, OR, USA.
USDA Forest Service, 1933. Report on the Pacific Northwest Forest Experiment Station for the Month of October. On file: USDA For. Serv. Pac. Northwest Res. Stn., Portland, OR, USA.
USDA Forest Service, 1937. Report on the Lookout Mountain Unit of the Pringle Falls Experimental Forest. On file: USDA For. Serv. Pac. Northwest Res. Stn., Portland, OR, USA.
USDA Forest Service, 2009. Climate Change Resource Center. US Department of Agriculture, Forest Service, Climate Change Resource Center. Washington, D.C., USA (http://www.fs.fed.us/ccrc, 10 Sept. 2009).
USDA, NRCS, 2009. The PLANTS Database. National Plant Data Center, Baton Rouge, LA, USA (http://plants.usda.gov, 10 Sept. 2009).
USDI and USDA, 2006. Protecting People and Natural Resources: A Cohesive Fuels Treatment Strategy. U.S. Department of the Interior and U.S. Department of Agriculture, Forest Service.
Youngblood, A., 1995. Research publications of the Pringle Falls Experimental Forest, central Oregon Cascade Range, 1930 to 1993. In: USDA For. Serv. Gen. Tech. Rep. PNW-GTR-347, Pac. Northwest Res. Stn., Portland, OR, USA, 45 pp.
Youngblood, A., Johnson, K., Schlaich, J., Wickman, B., 2004a. Silvicultural activities for special places in Pringle Falls Experimental Forest, central Oregon. In: USDA For. Serv. Gen. Tech. Rep. RMRS-P-34, Rocky Mount. Res. Stn., Fort Collins, CO, USA, pp. 31–48.
Youngblood, A., Max, T., Coe, K., 2004b. Stand structure in eastside old-growth ponderosa pine forests of Oregon and northern California. For. Ecol. Manag. 199, 191–217.
Youngblood, A., Metlen, K.L., Coe, K., 2006. Changes in stand structure and composition after restoration treatments in low elevation dry forests of northeastern Oregon. For. Ecol. Manag. 234, 143–163.
Youngblood, A., Wright, C.L., Ottmar, R.D., McIver, J.D., 2008. Changes in fuelbed characteristics and resulting fire potentials after fuel reduction treatments in dry forests of the Blue Mountain, northeastern Oregon. For. Ecol. Manag. 255, 3151–3169.
Zhang, J., Oliver, W.W., Busse, M.D., 2006. Growth and development of ponderosa pine on sites of contrasting productivities: relative importance of stand density and shrub competition effects. Can. J. For. Res. 36, 2426–2438.