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The Level-of-Growing-Stock (LOGS) study on thinning ponderosa pine forests in the US West: A long-term collaborative experiment in density management

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Abstract: The Levels-of-Growing-Stock study for ponderosa pine was a collective effort among western Research Stations within the US Forest Service. The experiment was established to test sustainable productivity across a wide range of densities by periodically thinning the plots. Beyond the original purposes for wood production, contemporary applications of these long-term studies have been to determine stand density effects on (*i*) both overstory and understory responses to stand development of even-aged ponderosa pine, (*ii*) biomass accumulation and carbon sequestration, (*iii*) plant diversity and wildlife habitats, and (*iv*) forest resiliency to insects and pathogens, droughts, and wildfires. Furthermore, these installations have served as a showpiece for the public and natural laboratories for professional foresters and students. For the past half century, the study has helped guide land managers and stakeholders on public and private lands about the value of thinning in overstocked young stands of ponderosa pine across its range. We hope that it will continue to serve as a springboard for addressing future issues facing forest management.

Keywords: LOGS; long-term experiment; *Pinus ponderosa*; stand density; sustainable yield

Forests are increasingly being relied upon as sources of economic, biological, and spiritual restoration by an expanding population (Diaci et al. 2011). Managers must account for more complex interactions while satisfying often competing demands, frequently facing situations with no obvious precedent (Brang et al. 2014). Depending upon the ecosystem and history of anthropogenic influence, there may exist historical examples of natural forest dynamics that can guide management decision-making (Brang 2005). Historical stand dynamics may not, however, adequately reflect current and future conditions in every situation (O'Hara 2016).

Short-term studies, even retrospective chronosequences, can be constrained by a limited set of ecological and climatic influences. Recently, large plots ("marteloscopes") have been set up to provide a network of knowledge transfer activities (Soucy et al. 2016) and, while interesting, rely on modeling to predict future stand structures over time. Continuous inventories of managed forests can provide valuable knowledge but are often influenced by the exigencies present at the time of each treatment and do not always provide a systematized picture that can aid current and future decision-making.

In light of this, there is still a place in the US and Europe for long-term systematic studies that can provide more relevant information for foresters managing for distant time-horizons, and yet that have probative value under today's conditions (Schütz 1999; Pretzsch 2006; Pretzsch et al. 2014). Sometimes, an objective like profitability or volume

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or some type of structure is the goal and the optimal treatment interval is determined (e.g., Pukkala et al. 2011). In other cases, like the growing stock level (*GSL*) studies discussed here, treatment intervals are fixed, and the treatment intensity is varied. The advantage of the latter approach is that there are examples for a range of potential operational alternatives.

Over the course of forest management in the United States, and for that matter world-wide, there has been the need to understand and predict how forests develop and the amount of timber they produce (Schlich 1904; Meyer 1938). Along with the prediction of yield its regulation on a sustainable basis became the focus of both public and private forest managers throughout the United States (Pearson 1950).

Ponderosa pine (*Pinus ponderosa* P. & C. Lawson) forests throughout western North America provided abundant amounts of wood for mining, railroads, and town and city infrastructure. By the mid and late 1800's, large volumes were harvested in northern California, Idaho, and western South Dakota (Bahre, Bloom 2003; Gaines, Kotok 1954; Myers 1967). In addition to providing large amounts of wood, ponderosa pine forests are a source of forage for cattle, provide wildlife habitat, water resources, and abundant recreational opportunities.

Good forest management decisions depend on knowing how forests respond to different treatments. At the turn of the 20th century, there was a need to quantify how young ponderosa pine stands would respond to different levels of thinning and how individual trees and stands might develop over time under those different thinning treatments. Ponderosa pine thinning trials on even-aged stands began early in the 1900s both in the Black Hills (1906) and in Idaho (1911). Bates (1919) suggested that 7 500 ponderosa pine saplings per hectare will fully realize the full capacity of the land, however 3 000 trees·ha^{-1} assured the greatest increment per tree. Seven-year results from the Idaho trial indicated that thinning a stand to about a 1.8-m spacing by removal of the diseased, defected, and suppressed trees yielded a 65% increase in the rate of diameter growth of the residual trees (Korstian 1920). Several other test plots were thinned from 1925 to 1931, but major "stand improvement" treatments including thinning, pruning, and general cleanup or sanitation cutting awaited the arrival of the Civilian Conservation Corps program of 1933–1941 (Mowat 1953). The most extensive thinning of ponderosa pine was in the Black Hills (Stuart and Roeser 1944), where some 100 000 ha were covered. Some of the general results from tracking a subsample of plots were that thinning had a positive effect on diameter growth, but either neutral or negative effect on basal area of residual stands (Pearson 1936; Krauch 1949).

These earlier results were mostly from individual experiments without replication of treatments, precommercially thinned only once, and usually on a single site (Gaines, Kotok 1954; Mowat 1953; Myers 1958), which limited the applicability of these results in other locations. More importantly, these early studies did not test low reserve densities nor did they track long-term stand development. For example, by measuring and analyzing a density study established by Roeser and Black Hills National forest personnel in 1931, Myers (1958) suggested thinning stands to about 1 360 trees·ha^{-1} when average diameter was 2.5 cm, 1 050 trees·ha^{-1} when diameter was 5.0–7.6 cm, and 740 trees ha^{-1} when diameter was 12.7 cm, if sawlogs were to be produced with one commercial thinning. These recommendations differed from what Stuart and Roeser (1944) suggested for thinning trees < 15 cm diameter to 2 220 trees·ha^{-1}. It appeared that as more information became available, managers were encouraged to thin to lower residual stand density levels. Dissimilar experimental designs and measurements that were incomplete or based on specific products further restricted comparability. A long-term, well-designed experiment replicated on multiple sites should provide such an answer. As a result, Myers (1967) designed a study to obtain ponderosa pine growth information over a range of stand and site conditions and with a minimum of operational restrictions. He divided the range of ponderosa pine in the western United States into five regions and proposed similar ponderosa pine growing stock levels be installed, treated, and measured to provide a comprehensive understanding and knowledge for managing ponderosa pine forests.

Research scientists from the four western Forest and Range Experiment Stations existing at that time (Rocky Mountain, Intermountain, Pacific Northwest, and Pacific Southwest) in the USDA Forest Service discussed and agreed on a so-called westwide Levels-of-Growing-Stock (LOGS) study at Berkeley, California on February 27–28, 1963 using Myers' design. The original proposal called for a duration of 20 years with the following objectives (My-

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ers 1967): "to determine (*i*) optimum stand densities for maximum growth of usable wood per tree and per hectare over a range of site qualities and average diameters and (*ii*) growth and yield obtainable with repeated thinning." Because stand density was a sole treatment on usable wood in the design, effect of other factors such as stand structure on forest productivity was not tested (but see O'Hara 1989, Long, Smith 1990, Curtis et al. 1997).

The goals of this paper are to (*i*) reintroduce people to this study and its corresponding six installations, (*ii*) reiterate the major early findings and their guidance to forest management, and (*iii*) suggest some possible usefulness of these installations to address the contemporary issues in managing ponderosa pine forests for resiliency under climate changes. Across the world, especially in Europe and North America, these long-term permanent research plots have become the foundation to address the long-term silvicultural questions that could not be answered by the national forest inventory (Didion et al. 2009; Zhang et al. 2013a, 2019a; Pretzsch et al. 2019). We hope to interest more scientists from other disciplines across the world to use these installations to answer the different scientific and management questions for the even-aged ponderosa pine forests.

ORIGINAL STUDY PLAN

The five "provinces" selected for the study represent five physiographic ranges that differ in many respects (Figure 1). Physiography ranges from the

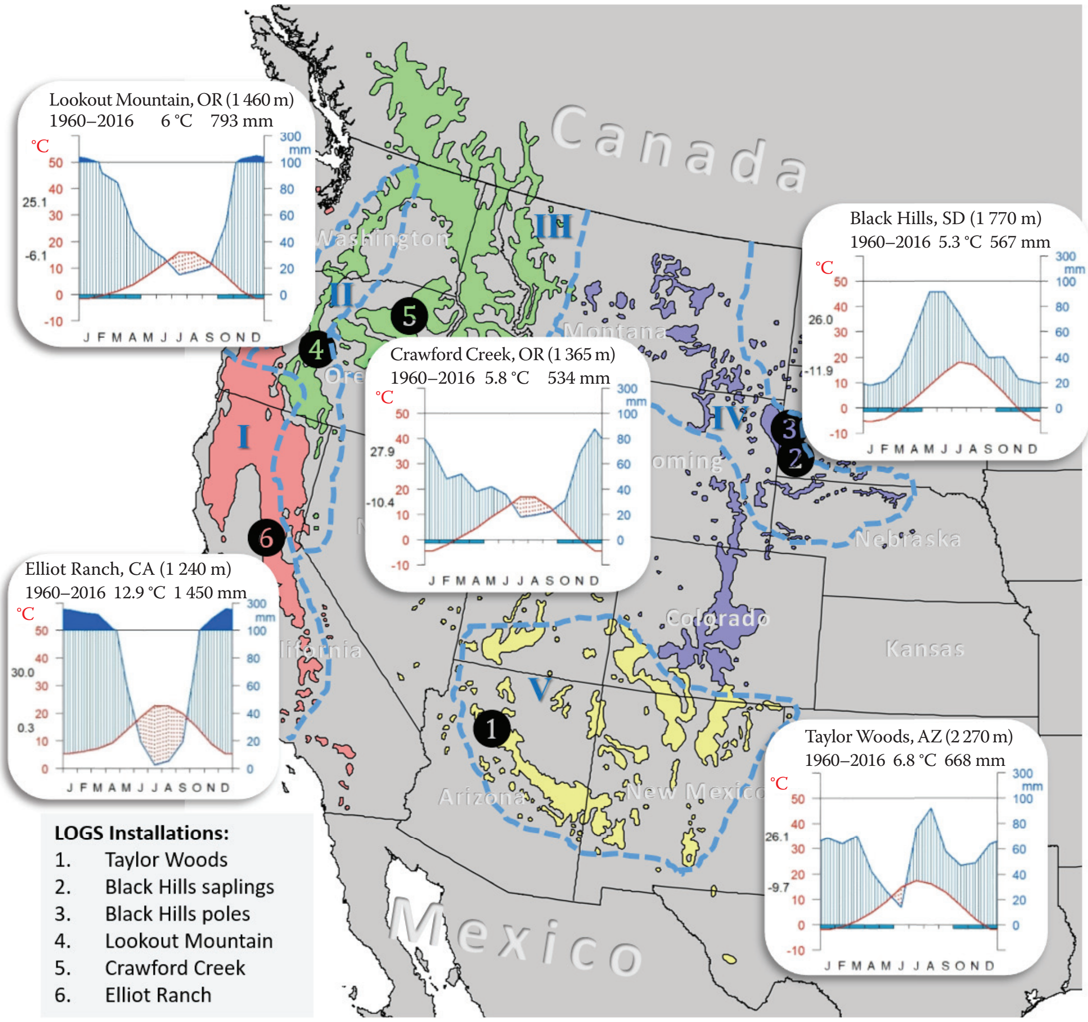

Figure 1. Natural ranges of ponderosa pine and chronological installation locations for study of levels-of-growing-stock (LOGS); colored background map with approximate extent of the different *Pinus ponderosa* subspecies is adapted from USGS (1999); the dash lines and roman numerals were five physiographic ranges originally identified for the study (Myers 1967); climate data for the Walter (1963) climatic diagrams are from PRISM Climate Data (http://prism.oregonstate.edu/)

https://doi.org/10.17221/72/2020-JFS

uplift of the Black Hills of South Dakota to the Coconino Plateau of Arizona, the Blue Mountains and Cascade Range of Oregon, and the Sierra Nevada of California. Temperature and precipitation vary greatly among these sites. Some provinces are without summer precipitation, while others receive most of their annual precipitation during the growing season as shown in the Walter (1963) climate diagrams inside Figure 1.

Growing stock level (*GSL*) is defined by relationships between basal area and average stand diameter at breast height (*DBH*). *GSL* is originally defined as the basal area per 0.4 ha (1 acre) when the mean diameter equals 25.4 cm (10 inches). As a result, *GSL* provides a target tree size (i.e., 25.4 cm) at a specific basal area and provides suggested tree densities for mean *DBH*s less than 25.4 cm. After the plot mean *DBH* is over 25.4 cm, *GSL* levels cannot precisely characterize plot basal area anymore because of the basal area growth that each tree adds over time. But, it becomes a relative treatment of *BA* levels and therefore, the original *GSL* levels with square feet per acre were retained in this paper (Table 1). Myers (1967) used information from Bates (1919), Harmon (1955), Myers (1958), and the 1961 thinning guide of the Black Hills National Forest to estimate the residual basal area that appeared best for each average stand diameter (Figure 2). Based on Myers' (1967) study proposal, stand densities to be retained after thinning were specified as a series of *GSL*s from 6.9 $m^2 \cdot ha^{-1}$ (30 $ft^2 \cdot acre^{-1}$) to 36.7 $m^2 \cdot ha^{-1}$ (160 $ft^2 \cdot acre^{-1}$) at different installations (Table 1). To obtain maximum tree and density uniformity within each plot, square-, rectangle-, and/or parallelogram-shaped plots were possible at each installation. During plot establishment, dominant and codominant trees of high vigor, with long full crowns and straight boles, or trees with a demonstrated capacity for rapid growth were chosen to be retained when the plots and buffers were thinned to achieve the specific *GSL*s at each site. Following the installation, all trees were tagged and measured for *DBH* to the nearest 0.25 cm. Tree damage and diseases were also noted. Various sampling schemes have been used to select trees for total height and height to the living crown, measured to the nearest 30 cm. Total stem volume was obtained either by the use of local volume tables or by the volume equations based on measurements with an optical dendrometer.

SITE CHARACTERISTICS AND TREATMENT MAINTENANCES

Despite an original call for combinations of four tree-size classes from small saplings to large poles on areas of three site qualities of high, medium, and low to be sampled within each province, it appeared the intended design was not achieved due to various reasons such as unavailable stands, not enough resources, or other factors (Oliver 2005). However, between 1962 and 1969 six installations were even-

Table 1. Installations in the west-wide levels-of-growing-stock study for even-aged ponderosa pine

Physiographic Province	Location	*SI*	Size class	*GSL*	Stand origin	Established		Earliest publication
						year	stand age	
Coconino Plateau, Arizona	Taylor Woods	19	small poles	30, 60, 80, 100, 120, 150	Natural	1962	43	Schubert 1971
Black Hills, South Dakota	Black Hills Saplings	17	large saplings	20, 40, 60, 80, 100, 120	Natural	1964	63	Boldt, Van Deusen 1974
Black Hills, South Dakota	Black Hills Poles	17	small poles	20, 40, 60, 80, 100, 120	Natural	1964	63	Boldt, Van Deusen 1974
East-side Cascade Range, Oregon	Lookout Mountain	28	large poles	30, 60, 80, 100, 120, 150	Natural	1966	65	Barrett 1983
Blue Mountains, Oregon	Crawford Creek	18	small poles	30, 60, 80, 100, 120, 140	Natural	1967	60	Cochran, Barrett 1995
West-side Sierra Nevada, California	Elliot Ranch	42	small poles	40, 70, 100, 130, 160	Plantation	1969	20	Oliver 1979

SI – site index in meters at 100 years (Meyer 1938); *GLS* – growing stock levels, we kept the targeted *GSL* level numbers with English unit ($ft^2 \cdot ac^{-1}$) to avoid confusion with the definition of the term (1 $ft^2 \cdot ac^{-1}$ = 0.2296 $m^2 \cdot ha^{-1}$).

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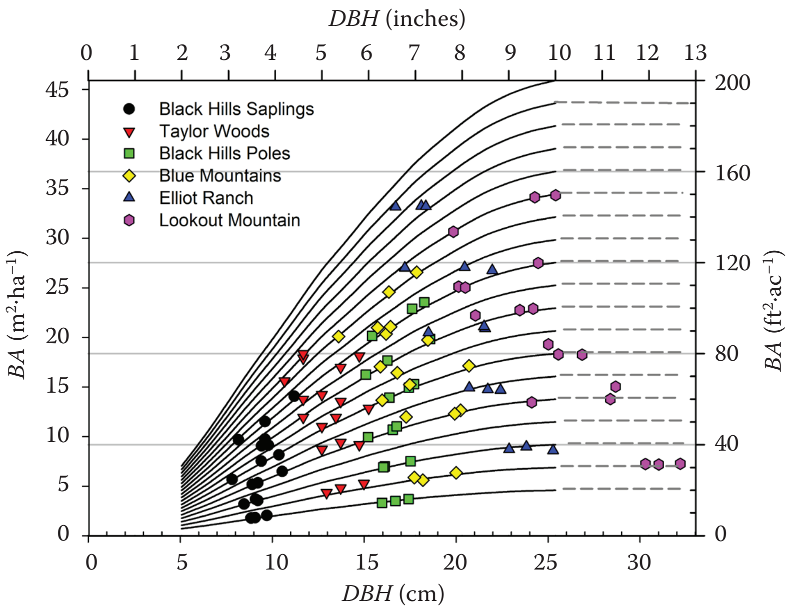

Figure 2. Residual basal area (*BA*) and average diameter at breast height (*DBH*) for each plot after initial thinning in the six installations of the Ponderosa Pine levels of growing stock study

solid lines represent the combinations of residual basal area and average *DBH* that were expected to allow plots to attain their nominal growing stock levels (*GSL*) level when average *DBH* reached 25.4 cm (10 inches, Myers 1967)

tually installed (Table 1). Measurements have been conducted every five years in general, between two and seven years occasionally. Later thinnings were not done as proposed due to growth rate variation and stand development among sites. Here is a summary of this information for each site.

Taylor Woods. Plots are located in the Fort Valley Experimental Forest on the Colorado Plateau in northern Arizona at an elevation of 2 266 m. Six *GSL* plots (Table 1), replicated three times, were installed in 43-year-old pure ponderosa pine on a gentle (4%), southwestern slope in 1962. Plot size varied from 0.3 to 0.5 ha with additional buffer strips (Ronco et al. 1985). The stand originated from seeds that germinated in 1919 after the exceptional seed crop from the previous year (Schubert 1971). Pre-treatment inventory showed an average stocking of 17 380 trees·ha^{-1}, basal area of 48.0 m^2·ha^{-1}, and diameter of 7.0 cm. (Ronco et al. 1985). The post-treatment included thinning these plots four times in 1972, 1982, 1992, and 2017. Tree measurements were generally conducted roughly every five years from 1962 to 2017.

Climate is semi-humid to humid, with cool temperature and early summer drought (Ronco et al. 1985). Average annual temperature is 6.7 °C. Mean daily temperatures range from –9.4 °C in January to 26.1 °C in July. Annual precipitation averages 56.0 cm. The Monsoon season in July and August is the wettest with about 1/3 of annual precipitation.

The soil is classified as a Typic Argiboroll, cool, fine montmorillonitic. It is deep and well drained, developing from a mixed alluvium derived from volcanic material, primarily basalt (USDA 1975).

Black Hills. Plots are located on the Black Hills Experimental Forest in western South Dakota at elevations of 1 706–768 m. Six *GSL*s (Table 1) for both sapling plots and pole-size plots were established in 63-year-old stands with three replications (18 plots in large saplings and 18 in small poles) in 1961 and 1962 on gentle topography flat to minimally sloping. The sapling plots were 0.1-ha in size with 10-m buffers around them and the pole plots were 0.2-ha in size with 14-m buffers. In 1978, three unthinned plots representative of the sapling plots and three unthinned plots representing pole-sized trees were established. The stand originated from disturbances by mountain pine beetles (*Dendroctonus ponderosae*) and/or wildfires of the late 1800’s (Boldt, Van Deusen 1974; Graham et al. 2019), which resulted in between 1 500 to 2 500 trees·ha^{-1} on the pre-treatment plots. The post-treatment included thinning these plots three times in 1968, 1973, and 1978. Tree measurements were conducted every 3-7 years from 1962 to 1998. All *GSL* plots had some trees removed in 1998 to achieve the desired structures. Unfortunately, all plots in both large saplings and small poles were subsequently lost to heavy mountain pine beetle infestation (Graham et al. 2019).

The study site has a continental climate with a mean annual temperature of 3.9 °C, maximum annual mean of 13.0 °C, minimum annual mean of –5.3 °C, and extreme temperatures of –44.0 °C and

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40.0°C. The mean annual precipitation is 51.1 cm with the majority falling in the spring and summer (cf. Graham et al. 2019).

Soils are within the Pactola-Rock Outcrop-Virkula Association which contain rock outcrops and deep, well drained, gently sloping to very steep, loamy soils formed in material weathered from steeply tilted metamorphic rock (Ensz 1990).

Lookout Mountain. Plots are located on the Pringle Falls Experimental Forest and adjacent Deschutes National Forest in central Oregon, east of the Cascade Range crest at elevations ranging from 1 405 to 1 603 m. All 18 plots were installed in a 65-year-old pure ponderosa pine stand on the south-facing slope of Lookout Mountain (Table 1). Six *GSL*s were randomly assigned to one of the three blocks. The plot size is 0.2-ha with additional 10-m buffer strips. The original stand was dense, with only 25% of total tree height in live crown (Cochran, Barrett 1999). Pre-treatment stand characteristics showed an average stocking of 2 830 trees·ha^{-1}, basal area of 55.1 $m^2 \cdot ha^{-1}$, and diameter of 16.0 cm. Post-treatment activities included thinning these plots twice back to original densities in 1975 and 1985. The latest thinning was conducted in 2012. All trees were measured every five years from 1965 to 2019.

Climate is continental, modified by proximity of the Cascade Range to the west and the Great Basin Desert to the east. Average annual temperature is 6.0 °C. Annual daily temperatures range from –3.8 °C in January to 25.1 °C in July. Annual precipitation averages 78.7 cm, of which most falls as snow in winter.

The soil is a deep, well-drained, cindery over medial (loamy) Typic Cryorthent formed from dacite pumice originating from the eruption of Mount Mazama (Crater Lake). The pumice averages 0.9 m deep and is underlain by sandy loam material developed in older volcanic ash containing some cinders and basalt fragments (Cochran, Barrett 1999).

Crawford Creek. Plots are located in the Blue Mountains on the Malheur National Forest in northeastern Oregon at elevations of 1 313–1 457 m. All 18 plots with six *GSL*s (Table 1), most being 0.2-ha (ranging from 0.16 to 0.30 ha) in size with additional 10-m buffer strips, replicated in three blocks, were installed in 60-year-old pure ponderosa pine on all aspects of slopes ranging from 6–29%. The pre-treatment stand was dense (Cochran, Barrett 1995), with an average stocking of 5 323 trees·ha^{-1}, basal area of 41.1 $m^2 \cdot ha^{-1}$, and diameter of 9.9 cm. After installation, the plots were thinned back to the original stand densities in 1977 and 1980. Measurements were conducted about every five years from 1967 to 2019.

The Blue Mountains are in the rain shadow of the Cascade Mountains and are predominantly influenced by Great Basin climatic patterns, resulting in warm and dry conditions. Average annual temperature is 5.8 °C. Annual daily temperatures range from –10.4 °C in January to 27.8 °C in July. Annual precipitation averages 53.3 cm, most of which falling as snow in winter.

Soils are well-drained loamy-skeletal associations with loam and clay loam surface layers 15 to 41 cm deep and 12 to 65% gravels and cobbles. The parent material is Mazama volcanic ash mixed with colluvium overlying colluvium and residuum derived from andesitic basalt (Cochran, Barrett 1995).

Elliot Ranch. Plots are located on the Tahoe National Forest, on the west slope of the northern Sierra Nevada of California at elevations of 1 222–1 271 m. All 15 plots with five *GSL*s (Table 1), being 0.2 ha with 10-m buffer strips, replicated three times, were installed in a 20-year-old plantation on gentle, south-facing slopes ranging from 3 to 10%. The trees were planted at a 1.8 by 2.4 m spacing following the Elliot Ranch wildfire and by age 20 had reached an average stocking of 2 224 trees·ha^{-1}, basal area 35.6 $m^2 \cdot ha^{-1}$, and diameter 17.8 cm (Oliver 1997). Post-treatments included re-thinning plots back to the original densities in 1974, 1979, and 1989. The latest thinning was conducted in 2014. All trees were measured every five years from 1969 to 2019.

The Mediterranean climate has typical hot, dry summers and mild, wet winters, with annual precipitation of 144.8 cm falling mostly as winter snow. Average annual temperature is 12.9 °C. Annual daily temperatures range from 0.3 °C in January to 30.0 °C in July.

Plots are located across an area containing three general soil types. Approximately half of the area is underlain by a Cohasset loam derived from volcanic rock, one-third by a Horseshoe gravelly loam (a Xeric Haplohumult developed from Tertiary Period river gravels) and the remaining one sixth by an alluvial soil not easily classified as to series. Depth to parent material is at least 1.5 m in all three soil types (Oliver 1997).

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FINDINGS TO FULFILL ORIGINAL OBJECTIVES

Regardless of the stand origin, site quality, and conditions prior to the experiment, the residual stands responded to thinning in general with more diameter growth in the low density plots versus the higher density plots (Figure 3). The slopes for *QMD* increment were steeper when the initial BA was lower than 18.4 $m^2 \cdot ha^{-1}$ (80 $ft^2 \cdot ac^{-1}$) during five years after installations. Similar trends (i.e., increased increment at low densities) were observed for basal area increment although the maximum yield point was highly variable among installations at 13.8–18.4 m^2 ha^{-1} (60–80 $ft^2 \cdot ac^{-1}$). Myers regarded the 18.4 m^2 ha^{-1} (80 $ft^2 \cdot ac^{-1}$) as "the best" basal area for trees with different diameter (Graham et al. 2019), which is confirmed by these installations at least for the first five years.

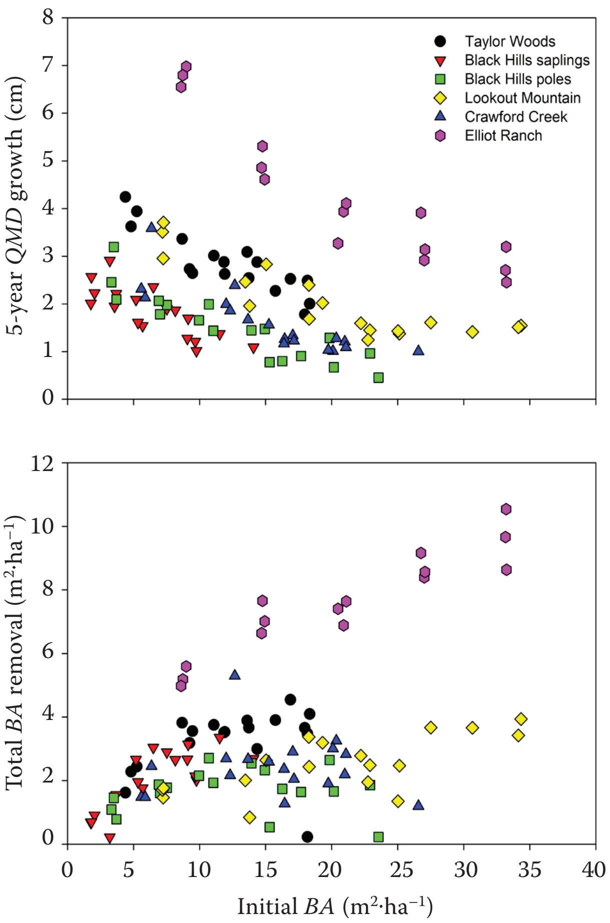

Figure 3. First 5-year increments of quadratic mean diameter (*QMD*) and basal area (*BA*) of ponderosa pine trees grown in each plot with varying basal areas at the beginning of plot installations at six levels-of-growing-stock (LOGS) sites

Site comparisons are difficult and may not provide useful information because of the confounding factors among soils, climate, origin of stands, stand age, sub-species, and genetic variation (Read 1980; Powers et al. 2005). Oliver and Edminster (1988) analyzed the 15- to 20-year treatment means from five of these installations (excluding Crawford Creek). Their general conclusion was that thinning markedly influenced growth; the residual stands were more responsive to thinning on the better sites than they were on poorer sites, which is true today. However, using individual plot data, Edminster (1988) concluded that periodic annual increments for *QMD*, *BA*, and volume per hectare were highly correlated with residual stand densities. Both analyses found a significant decline in volume production and the rapid attainment of merchantable-sized material with low residual stand densities. Due to a significant site difference, integrated models showed that site index explained the majority of variation for growth, whereas stand density or *GSL*, which was the core treatment, only provided a marginal explanation. Therefore, they cautioned readers about using results for stand density management from the combined data.

Nonetheless, the data obtained from each installation are of uniformly high quality, and results and conclusions drawn from them are sound. Further cross-site research on the density effect would likely benefit from a meta-analysis. In addition, the duration of density manipulation may be explored with these data because of a repeated thinning in these installations. For example, periodic annual diameter growth (*PAI QMD*) ranged from 0.86 to 0.38 cm per year between the lowest- and the highest density plots, respectively, at Taylor Woods during the first ten years (Ronco et al. 1985). It decreased during the second ten years to 0.76 cm in the lower density plots and to 0.25 cm per year in the higher density plots. The trends were very similar at Lookout Mountain (Cochran, Barrett 1999), Crawford Creek (Cochran, Barrett 1995) and Elliot Ranch (Oliver 1997) although absolute values differed among sites. By analyzing the three LOGS installations in Oregon and California using 45 years of data, Zhang et al. (2013c) found that pai *QMD* in California doubled that of *PAI QMD* in Oregon for almost every density plot. Besides diameter, predictive models of periodic annual increment of

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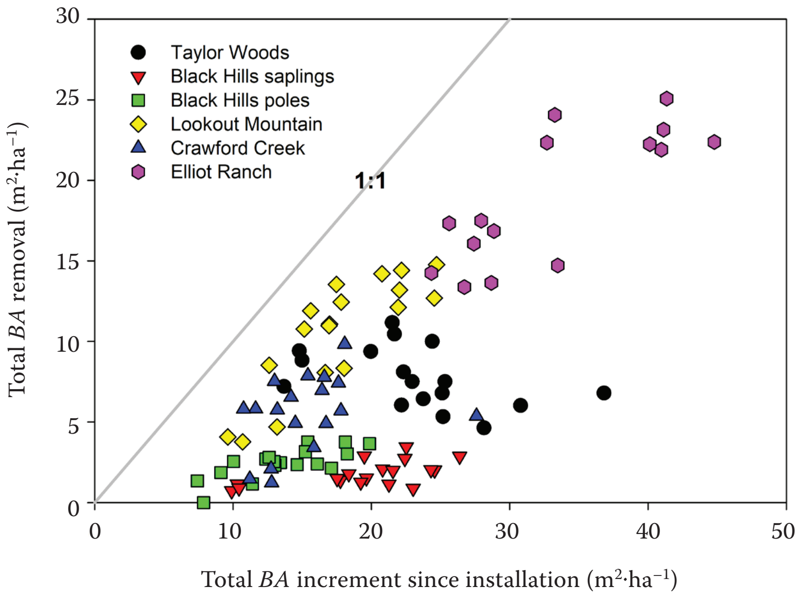

Figure 4. Total basal area (*BA*) removal from the plots versus total basal area increment since installations at six levels-of-growing-stock (LOGS) sites for the first 30 years (the 1:1 line indicates that growth equals removal)

height, basal area, volume, and sometimes board feet have been established at individual installations (Schubert 1971; Oliver 1979; Alexander, Edminster 1980; Barrett 1983; Ronco et al. 1985; Cochran, Barrett 1995; Graham et al. 1995; Cochran, Barrett 1999; Bailey 2008; Zhang et al. 2013b, c; Graham et al. 2019) and have guided foresters in ponderosa pine density management locally. Therefore, considering that the growth of usable wood was the management objective in the original plan, the first objective to find an optimum stand density for wood production has been achieved.

The second objective in the original proposal was to determine if sustained growth and yield was obtainable with repeated thinning. A simple answer is to calculate the difference between wood (basal area) removed from the thinning and wood increasing after the thinnings. Results from each site show that for all *GSL*s, growth always has been greater than the removals (Figure 4) regardless of stand density and site quality. In some *GSL*s at some sites, the removal was only half or less that of total growth, which suggests these forests can be sustainably managed. One caveat is that *GSL*s at the beginning of the study were far below the targeted stock levels except for some *GSL*s at Elliot Ranch and Lookout Mountain, which might cause the removal to be much less than the growth. Furthermore, after these plots reached a *QMD* of 25.4 cm, trees have grown more than targeted *GSL* during most years except for the year after the thinning.

Besides the growth, the installations have been used to study the stand density effect on wood quality (Markstrom et al. 1983; Vaughan et al. 2019), the costs and returns from pruning stands that had been thinned to various stand densities (Smith et al. 1988), the chemistry of green foliage and forest floor (Wollum, Schubert 1975), and contribution to a database for simulating potential production for various combinations of stand density, site index, age and thinning schedule (Myers 1966; Alexander, Edminster 1980; Ritchie et al. 2012).

FINDINGS TO ADDRESS CONTEMPORARY FOREST MANAGEMENT ISSUES

Since the LOGS were installed, the objectives for managing ponderosa pine forests for wood production have been broadened to include multiple uses. Therefore, the lifespan of these plots has been extended far beyond the original proposal and have been used to address many contemporary management issues. However, because of the problem presented as a caveat earlier, that is, that the *GSL*s at the beginning were below target stocks, the *GSL* levels could not represent the exact basal areas experienced by these trees. Therefore, the real basal areas or stand density for each plot at the beginning of each measurement period or average within period were recommended as we did in Figure 3, and as did Cochran and Barrett (1995; 1999) and Zhang et al. (2013 b, c).

Forage and understory production. Ponderosa pine forests provide important habitat for various wildlife species and forage for livestock grazing.

https://doi.org/10.17221/72/2020-JFS

Lowering stand density from these LOGS installations has been reported to increase understory production without significant invasion of exotic species (Uresk, Severson 1989; Zhang et al. 2013b). The understory production was asymptotic when *BA* of overstory trees was reduced to 5.1 $m^2 \cdot ha^{-1}$ at the Black Hills (Uresk, Severson 1989). Whereas in the Southwest, the asymptotic peak were reported as varying with 16.1 $m^2 \cdot ha^{-1}$ (Clary, Ffolliott 1966), 14.9 $m^2 \cdot ha^{-1}$ (Griffis et al. 2001), and 6.0 $m^2 \cdot ha^{-1}$ (Sabo et al. 2008); the discrepancy might be due to varied plant communities or/and microsite characteristics. In the Sierra Nevada, the peak of understory production appeared when *BA* of overstory was between 16.1 and 23.0 $m^2 \cdot ha^{-1}$ in the Elliot Ranch LOGS (Zhang et al. 2013b). In addition, for understory grasses and shrubs, reducing stand density will enhance natural regeneration of conifer seedlings, especially the shade intolerant conifer species (Oliver, Dolph 1992).

The Elliot Ranch LOGS also demonstrated how to create complex species and stand structures in a mono-specific plantation. That has been of particular interest to observers because of the abundant regeneration of mixed conifers in the lower density plots and the interest in speeding development of more "natural" appearing forests.

Biomass and carbon sequestration. Since forests play a significant role in carbon sequestration and storage, the impact of stand density management on carbon pools must be understood for foresters to effectively design a management regime that captures and stores the most atmospheric CO_2 by forests. By calculating total aboveground net primary production, Zhang et al. (2013c) reported that total basal area production did not differ substantially among stand density regimes except perhaps for the lowest stand density regimes by year 2009. Of management significance is the fact that *BA* production for live trees was the highest for plots with *GSL* 70 at Elliot Ranch. With an availability of all tree inventories (dead or live) including the original and later thinnings for these extended datasets, we can calculate aboveground biomass and subsequent carbon for individual trees with the available allometric equations for ponderosa pine (Zhang et al. 2010). Figure 5 shows that greatest total aboveground biomass (dry matter – DW) and carbon sequestration were in the original plots targeted at *GSL* 80 in Lookout Mountain (115.6 Mg $DW \cdot ha^{-1}$ or 57.8 Mg $carbon \cdot ha^{-1}$), *GSL* 60 in Crawford Creek (123.6 Mg $DW \cdot ha^{-1}$ or 61.8 Mg $carbon \cdot ha^{-1}$), and *GSL* 70 in Elliot Ranch (385.0 Mg $DW \cdot ha^{-1}$ or 180.1 Mg $carbon \cdot ha^{-1}$) (Zhang et al. 2013b). All were at lower end of the originally targeted *GSL* plots. Biomass and carbon are not calculated at other sites due to non-available data of initial thinning.

A complete forest carbon pool must consider wildfires in the fire-dominant ecosystems where ponderosa pine grows (Powers 2010; Zhang et al.

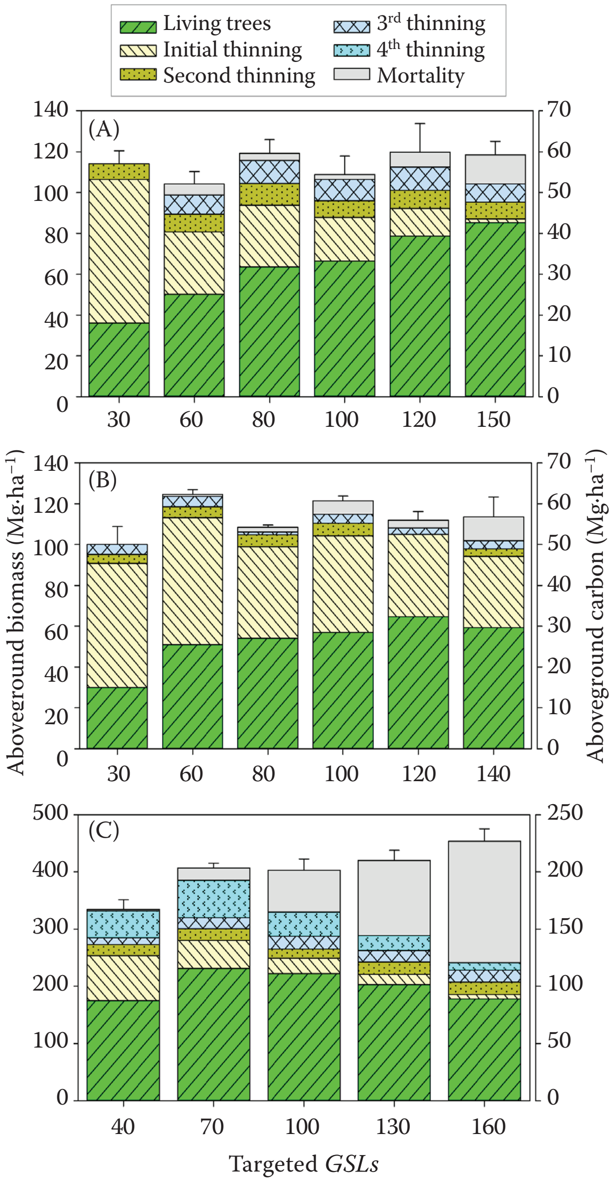

Figure 5. Cumulative gross production of aboveground biomass and carbon in various originally targeted growing stock levels (*GSLs*) from the ponderosa pine levels-of-growing-stock (LOGS) at Lookout Mountain (A), Crawford Creek (B), and Elliot Ranch (C) up to 2014

https://doi.org/10.17221/72/2020-JFS

2010). Large diameter trees with high stature and thicker bark are most likely to survive a wildfire and therefore represent a more stable form of carbon storage than smaller trees (Zhang et al. 2010; Earles et al. 2014). Because trees grown on lower density plots are generally much larger than trees on higher density plots, lower density plots provide more such carbon than the high-density plots.

Forest mortality. The three major forces threatening ponderosa pine forests are insect and disease outbreaks, drought, and wildfires. Throughout western North America, several *Dendroctonus* species are important ecosystem components. Their periodic outbreaks have the potential to cause widespread mortality in mature forests within large areas (Fettig et al. 2007). In California, *Dendroctonus* spp. cause considerable mortality in ponderosa pine forests (Oliver 1997). Using Reineke's (1933) Stand Density Index (*SDI*), which measures relative stand density in terms of the relationship of a number of trees to stand quadratic mean diameter, as an independent variable, Oliver (1995) predicted that self-thinning started when *SDI* reached 568 trees·ha^{-1} and significant mortality occurred when *SDI* reaches 900 trees·ha^{-1} based on even-aged ponderosa pine data from permanent research plot including LOGS plots in California. After new data became available, Zhang et al. (2013a) found that these *SDI* values were higher on sites with higher site index than on sites with lower site index. By re-analyzing data from LOGS installations at Crawford Creek, Lookout Mountain, and Elliot Ranch, Zhang et al. (2013c) found that bark beetle-caused mortality was positively related to stand density, as has been consistently found in previous studies (Oliver 1995; Cochran, Barrett 1995; 1999). Although bark beetles follow volatile resins after ponderosa pine trees are cut (Oliver 1995), trees in the lowest density plots were rarely killed by bark beetles, regardless of site index. Although there are numerous stand- and landscape-level factors influencing bark beetle activity and outbreaks, lower mortality rates in the low-density plots suggested that thinning can confer some resistance to bark beetles (Figure 6).

The rationale that trees in the lower density plots are more resistant to bark beetle attack is that

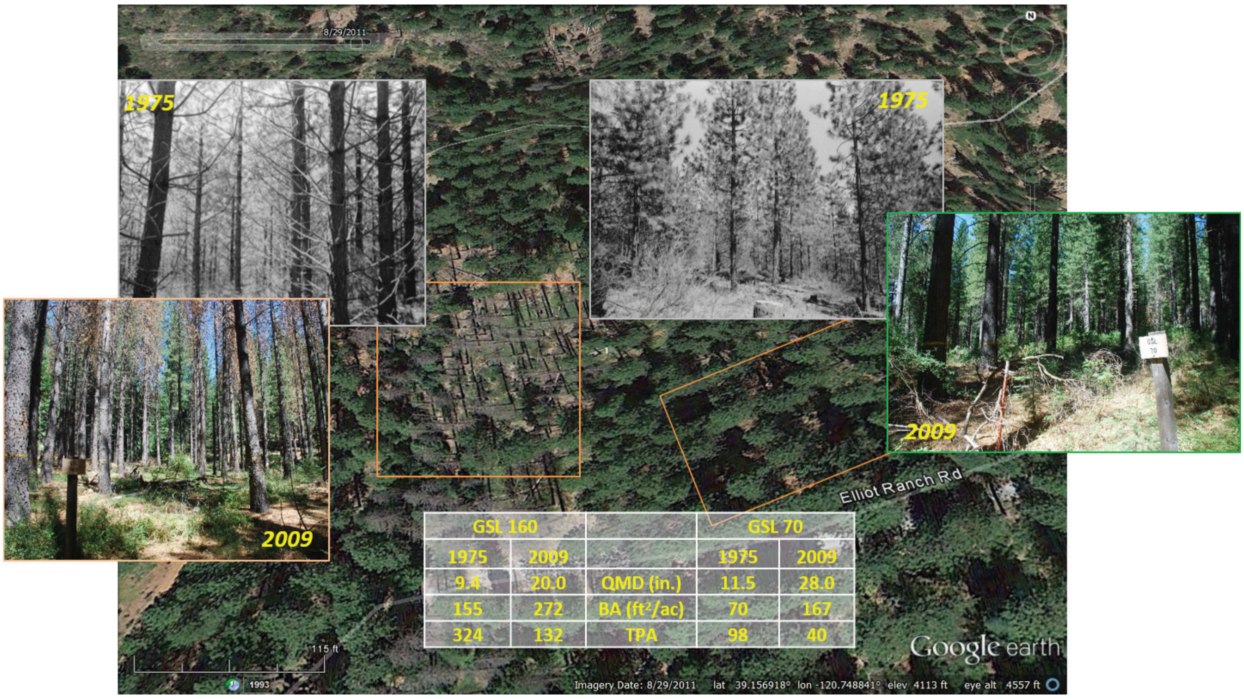

Figure 6. Two side-by-side plots with originally targeted to growing stock levels (*GSL*) – *GSL* 160 on the left and *GSL* 70 on the right at Elliot Ranch levels-of-growing-stock (LOGS) study near Foresthill, California

(the two 1975 photos were taken at the sixth year after the installation and the first rethinning; the 2009 photos were taken after a 2008 heavy beetle infestation killed most trees on the *GSL* 160 plot, but not a single tree on the *GSL* 70 plot; the background is from google earth in 2011)

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lower densities enhanced tree vigor with attendant increase in water and nutrient availability and an increase of phloem thickness and resin production (Kolb et al. 1998). Furthermore, water use efficiency and drought tolerance were also increased in the lower density stands (McDowell et al. 2006). The behavior of beetles themselves and influence of climate on their activity (Raffa et al. 2008) were not tested in these installations.

Mechanical damage intended to simulate wind storm effects (e.g., Cooper-Ellis et al. 1999) or wildland or prescribed fire was not used to test the resilience to abiotic disturbance in these plots because of the potential to compromise the original objectives when trees were killed or damaged by such disturbances. Given the history of frequent wildfires in this region, the stands with fewer and larger diameter trees should be more resistant to fire damage and subsequent mortality. By running a fire model with typical summer weather conditions for two densities at Elliot Ranch, Zhang et al. (2010) estimated tree mortality to be 36.6% in the *GSL* 70 plots and 61.5% in the *GSL* 160 plots at age 55. These were very conservative estimates because the dead trees had been removed from the plots and therefore were not counted as hazardous fuels that had been about 210 $Mg \cdot ha^{-1}$ (Figure 5). In the spring of 2018, a wildfire burned through one of *GSL* 70 plots at Elliot Ranch and did not kill a single tree, providing direct evidence.

LOOK FOR THE FUTURE

Fifty years ago, the plan was expected to run for 20 years. For the past half century, trees continued to grow but plot size had not changed, which may limit our ability to track overstory tree growth and development without the edge effect. Furthermore, further thinning of the lower reserve densities is no longer possible in most installations in order to keep at least 12 trees on the 0.2-ha plots. Nonetheless, a lot of scientific questions could be addressed from these installations. For example, the role of stand density in climate change mitigation can be tested with tree ring data from these sites (Zhang et al. 2019a). The advantages of using these trees compared to trees in a natural stand are (*i*) every tree has been tagged since the installation, (*ii*) tree positions are known, and more importantly (*iii*) dynamics of their neighbors when they died or were rethinned are recorded. These are included in the five unique features of long-term plots as compared to temporary plots or ecological surveys as summarized by a group of European forest scientists (Pretzsch et al. 2019).

Another potential use is to study soil microbes and/or soil chemistry. Although analyses of overstory trends is confounded by small plots, soils may not be so influenced. In addition, since the objectives of growth and yield have been reached, researchers could introduce fire to study the influence of stand structure on fire behavior (Zhang et al. 2019b). Long-term responses of understory diversity and development to stand density will always be an interesting topic and can be studied in these plots.

Finally, the outreach value of these installations cannot be underestimated. Since these plots were installed, they have become showpieces to the public, a real laboratory for forestry students, and training spots for professional foresters. For example, the Elliot Ranch LOGS have been visited by members of the California Forestry Association, California Certified Foresters, California Homeowner Association, California Pest Council, Advanced Silvicultural Class (US Forest Service internal certification program), Sierra-Cascade Forest Vegetation Intensive Management Research Cooperative, among others.

Although the scientists involved in establishing the installations have moved on, the commitment to maintain the study remains firm. The Rocky Mountain Research Station continues to maintain the Taylor Woods site although the Black Hills installations were lost to mountain pine beetles (Graham et al. 2019). The Pacific Southwest Research Station has assumed responsibility for Lookout Mountain, Crawford Creek, and Elliot Ranch. Now, we must draw interest from others to pass the baton to next generations.

As Oliver (2005) stated, "the major reason for the longevity of this west-wide LOGS study is the foresight of the original planners in testing a range of stand densities far beyond those practiced at the time, thus providing a demonstration of the long-term stand development of even-aged ponderosa pine applicable to many current management objectives".

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