USDA
United States Department of Agriculture

Differing Ponderosa Pine Forest Structures, Their Growth and Yield, and Mountain Pine Beetle Impacts: Growing Stock Levels in the Black Hills

Russell T. Graham, Lance A. Asherin, Theresa B. Jain, L. Scott Baggett, Michael A. Battaglia

2004

1964

2014

Forest Service

Rocky Mountain Research Station

General Technical Report
RMRS-GTR-393

June 2019

Graham, Russell T.; Asherin, Lance A.; Jain, Theresa B.; Baggett, L. Scott; Battaglia, Michael A. 2019. **Differing ponderosa pine forest structures, their growth and yield, and mountain pine beetle impacts: growing stock levels in the Black Hills.** RMRS-GTR-393. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 102 p.

Abstract

Clifford A. Myers conceived the ponderosa pine growing stock levels (GSL) study in 1961 and completed installation of the study in 1963 in western South Dakota on the Black Hills Experimental Forest (BHEF). The GSL concept was intended to help plan, implement, and illustrate tree thinning strategies (from below) in even-aged stands. A GSL is the suggested tree density (i.e., trees and basal area per acre) based on d.b.h. that can be tended to produce a desired basal area per acre (e.g., 80, 100, 120 square feet) when the mean d.b.h. is 10 inches. Plots representing GSLs 20, 40, 60, 80, 100, and 120 were thinned and measured through 2014. The thinnings that occurred in the GSL 80 plots showed the most promise for producing commercially sized trees and volumes through 2010. Unfortunately, by 2014, mountain pine beetles killed trees in all of the plots and ended the study.

Keywords: mountain pine beetles, forest productivity, tree thinning response, product yield

Photo credits: All photos are from USDA Forest Service except those noted.

Cover photos: Pole plot 60 of growing stock level (GSL) 80 in 1964, 2004, and 2014 showing its tree and stand development and subsequent heavy tree mortality caused by mountain pine beetles.

Authors

Russell T. Graham is a Research Forester (Silviculturist) with the USDA Forest Service, Rocky Mountain Research Station, Moscow, Idaho. He started his Forest Service career in 1966 as a high school student working on the Bear Lodge Ranger District, Black Hills National Forest. His research activities have included the role that coarse woody debris plays in forests, large-scale ecosystem assessment and planning, describing northern goshawk habitat, and evaluating the impacts of major wildfires.

Lance A. Asherin is a Forester (Region-2 Certified Silviculturist) with the USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. He manages the long-term mensurational research studies in Arizona, Colorado, South Dakota, and Wyoming and is developing a wide range of silvicultural systems and methods for the dry and dry-mixed conifer forests of the Rocky Mountains.

Theresa B. Jain is a Research Forester (Silviculturist) with the USDA Forest Service, Rocky Mountain Research Station, Moscow, Idaho. Her research focuses on developing, implementing, and evaluating alternative silvicultural systems and methods for addressing integrated fuel treatments.

L. Scott Baggett is the Station Statistician with the USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado.

Michael A. Battaglia is a Research Forester with the USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. His research focuses on developing and implementing innovative management strategies that address the challenges and issues faced by forest managers.

Acknowledgments

Current and past staffs of the Black Hills National Forest assisted greatly in completing this project and, most importantly, for ensuring that the integrity of the Black Hills Experimental Forest was maintained and the GSL plots within it were preserved. Blaine Cook and Deanna Reyher of the Black Hills National Forest deserve special thanks, as well as all of the people that measured the GSL plots over the years. James Donley of the Rocky Mountain Research Station did an excellent job of preparing the references and his help is greatly appreciated as was Ben Bright's help with the maps. Patricia Cohn, Station Editor for the Rocky Mountain Research Station, Loa Collins, and Suzy Stephens deserve special thanks for producing the publication. Lane Eskew did an excellent job of editing this large document and added greatly to its content. Kathy Graham also supplied editing help which is greatly appreciated. We also are grateful for the effort our reviewers put into reading and improving this manuscript.

Contents

Introduction

For the last two centuries, managers and policy makers pursued methods for predicting forest growth and yield. During the sailing ship era, wood for boat building and especially poles for sail masts were highly desired (Evelyn 1664). The need to develop and plan for the acquisition of these materials was a national priority of many countries. Also, during the worldwide industrial revolution, wood was the major building material and railroads consumed large amounts of wood for ties and fuel (Egan 2009). Although wood was plentiful during these times, some individuals became aware that wood supplies were limited and there was a need to plan and predict the quantities of wood needed and available in the future (Freeman 2015).

By the late 1800s in Europe and India, forest sampling methodologies were developed and the field of silviculture was designing methods and systems that could be used to produce desired forest crops (Schlich 1904). Combining these two disciplines, along with the emerging field of mensuration, foresters developed procedures that predicted timber yield. Yield or volume predictions were produced for stands at different ages, for multiple tree species, and for different site qualities. Meyer (1934, 1938) first developed yield tables for uneven-aged stands of ponderosa pine (*Pinus ponderosa*) and then for even-aged stands. During this same era, yield tables were produced for Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) (McArdle and Meyer 1930; Meyer 1937). In contrast to these single-species yield tables, Haig (1932) produced tables for the western white pine (*Pinus monticola*) type, which included western white pine and associated species (e.g., western hemlock, western larch [*Larix occidentalis*] and Douglas-fir).

Beginning in earnest in the late 1800s and early 1900s, managers began to recognize the effect forest density had on both individual tree and stand growth. As a result, interest in stand density management began. Most often, this interest was limited, because large quantities of suitable timber were available in the Black Hills, however interest increased when large tracts of young and small trees existed. Because the Black Hills had a thriving mining economy in the early 1900s, different tree thinning trials designed to produce forest products and reduce wildfire hazard around towns and mill sites commenced (Krueger 1936; Pearson 1935). Given this history, the Black Hills were ideal for studying different tree thinning strategies that would add to the body of knowledge on the growth and yield of ponderosa pine forests.

Black Hills

On the eastern edge of the Rocky Mountains, the Black Hills are an isolated mountain range surrounded by prairie. They straddle the Wyoming and South Dakota border and are covered by ponderosa pine (*Pinus ponderosa* var. *scopulorum*) forests (fig. 1). They were formed by a regional uplift millions of years ago as a volcanic intrusion forced its way through limestone sediments. About three-quarters of this elliptically shaped domal structure lies in South Dakota and the other quarter, the Bear Lodge Mountains, is located in northeastern Wyoming (fig. 2). The Black Hills has a total land base of about 6,000 square miles, 125 miles from north to south and about 60 miles from east to west (3.84 million acres). White spruce (*Picea glauca*), quaking aspen (*Populus tremuloides*), lodgepole pine (*Pinus contorta*), and even limber pine (*Pinus flexilis*) occur. Nearly 1.5 million acres of ponderosa pine dominate the forests of the Black Hills with 884,900 acres occurring on the Black Hills National Forest (Boldt and Van Deusen 1974; Walters et al. 2013) (fig. 3).

Figure 1—Ponderosa pine (variety *scopulorum*) forests dominate the Black Hills of Western South Dakota and Northeastern Wyoming (circa 2009).

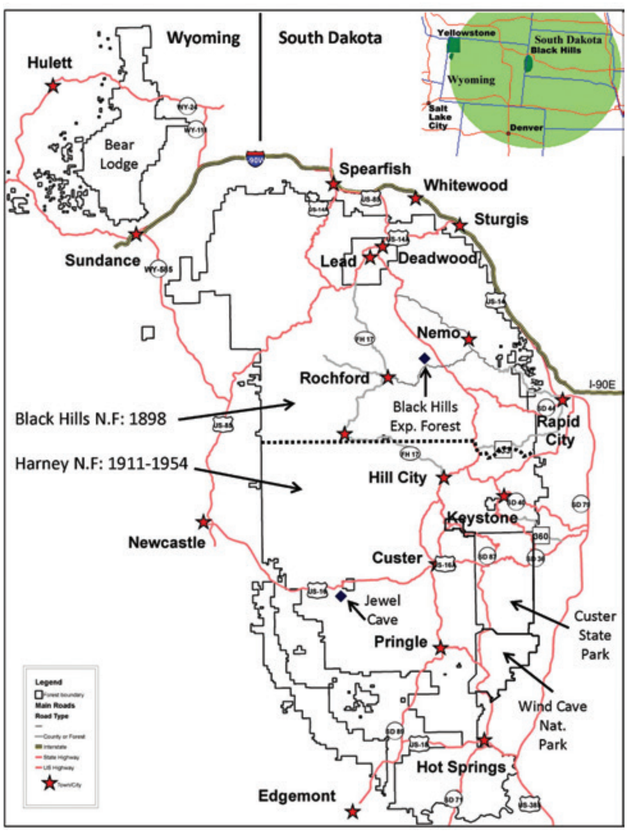


Figure 2—While the majority of the Black Hills National Forest occurs in South Dakota, a portion also occurs in the Bear Lodge Mountains of Wyoming. The Black Hills National Forest was established in 1898 and the Harney National Forest was established in 1911 and then was transferred to the Black Hills National Forest in 1954. Of historical note, the Sundance National Forest encompassing the Bear Lodge Mountains was established in 1908 and was transferred to the Black Hills National Forest in 1915.

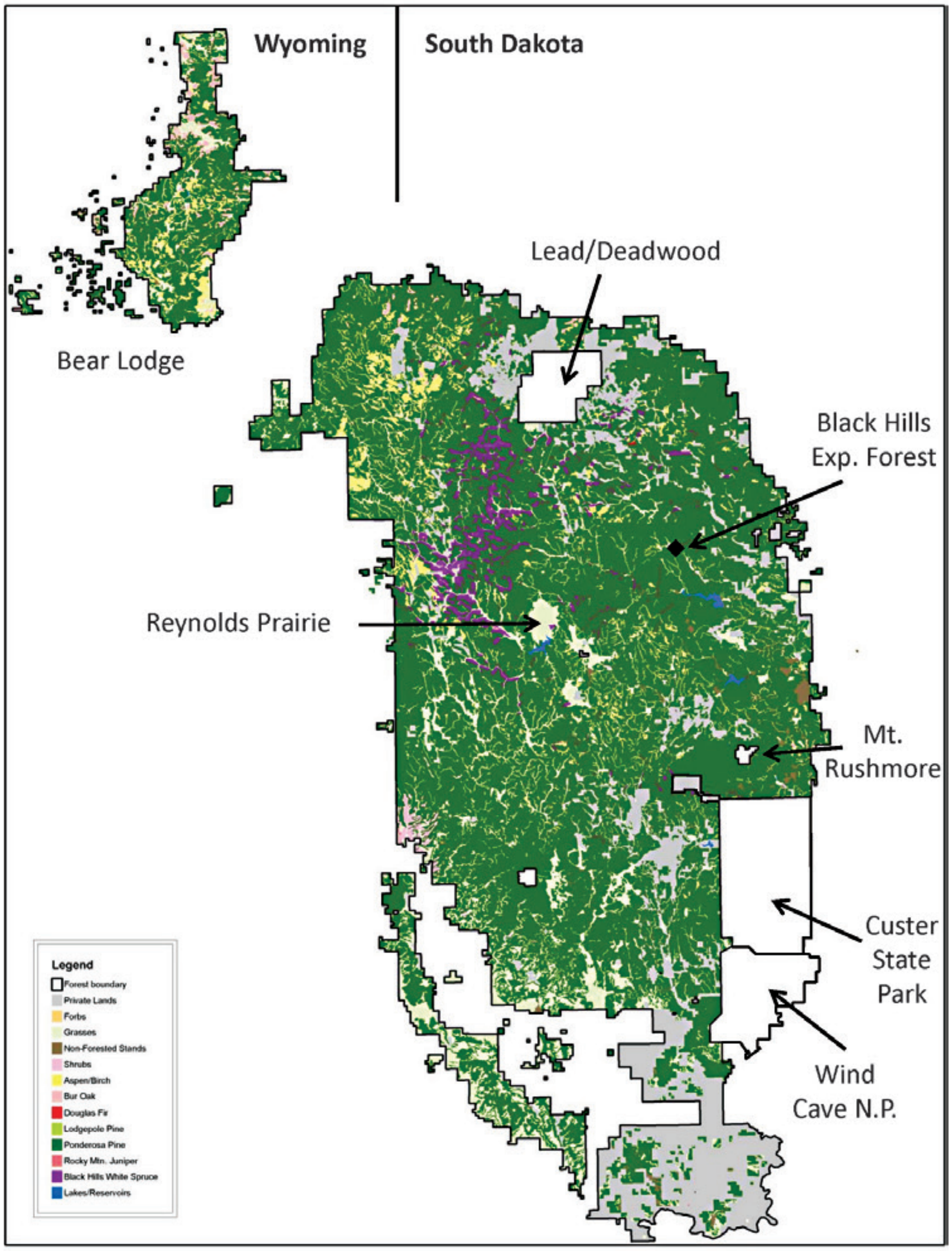


Figure 3—Ponderosa pine forests dominate the Black Hills vegetation, with a considerable amount of white spruce occurring in the north-central Black Hills and a variety of other conifers, hardwoods, meadows, and prairies comprising the remainder.

This amount of forest is remarkable in that the Black Hills has had over a century of consumptive use (Boldt and Van Deusen 1974). During this period, virtually all of the area's unreserved and operable forest acres have been cut over at least once, but many acres received multiple partial cuts. Large tracts that were logged free of regulatory restraints prior to establishment of the Forest Reserve in 1897 were commercially clearcut and stripped of all trees large enough to yield a mine timber or a railroad tie. Persistent harvesting, coupled with impacts of wildfire, insects, diseases, and wind have nearly eliminated the original old-growth stands on most of the commercial forest acres and left only a few scattered old-growth remnants on the remaining acreage (Boldt and Van Deusen 1974).

The unregulated harvest was controlled by the early 1900s and for approximately 50 years, a variety of partial cutting systems were used to manage the forests, resulting in highly heterogeneous forests containing a diversity of tree sizes arranged in a wide variety of mosaics (Harmon 1955). In the 1960s, forest management used more intensive practices that developed two and three tree age classes or canopies in many forests (Boldt and Van Deusen 1974; Boldt et al. 1983). Wildfires, bark beetles, and diseases killed trees during this period, adding forest complexity. Currently, the majority of the area is forested and, in many areas, densely covered with trees.

A key feature unique to these forests is the intermediate shade tolerance of ponderosa pine that promotes regeneration under partial shade and full sunlight. Ponderosa pine seed is produced almost every year with abundant crops every 2 to 5 years (Boldt and Van Deusen 1974). Also, the *scopulorum* variety of ponderosa pine that occurs in the Hills has many different traits than the ponderosa variety that grows on the west side of the Continental Divide (Potter et al. 2013). Frequent rain showers throughout the growing season, which lasts from early March to August, provides an environment that favors prolific ponderosa pine establishment (fig. 4).

In response to natural disturbances and because of the ease of regeneration that occurs in the Black Hills, the area has had one of the most consistent commercial timber harvest programs in the United States. The Black Hills Forest Reserve established on February 22, 1897, and the Organic Act signed in June of 1897 provided the means for selling of timber from public lands. Later that year the General Land Office received an application from T. J. Grier, Superintendent of the Homestake Mining company of Lead, South Dakota, to harvest all Norway pine (ponderosa pine) trees 8 inches and larger in diameter (d.b.h.) on approximately 5,120 acres near Nemo, South Dakota (Clow 1998; Freeman 2015). This Case One of commercial harvest in the Black Hills provided the impetus for studying tree thinning beginning in 1906 near where the harvest was occurring (figs. 2, 5A,B).

Figure 4—In the Black Hills, because of the spring and summer rains and abundant seed crops, ponderosa pine readily regenerates and carpets the forest floor in most locales.

(A) (B)

Figure 5—Timber harvesting began in the Black Hills near Nemo in 1898 with Case One, the first commercial timber sale on Federal property within the United States (A). Within this same area, Bates (1919) and others started various thinning trials (B).

Forest Tending

Over the course of forest management in the United States, and for that matter worldwide, there has been the need to understand and predict how forests develop and the amount of timber they can produce (Haig 1932; Meyer 1938; Schlich 1904). 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; Roth 1925). A key need in both yield prediction and yield regulation was the understanding of how different forest structures responded to treatments and how individual trees and stands developed in response to different treatments. And, because of prolific regeneration of ponderosa pine trees in the Black Hills, the need for such information was paramount. In both the South Dakota and Wyoming portions of the Hills, pine seedling densities exceeding 10,000 per acre after a disturbance are not extraordinary. Even though tree mortality from wind, snow, and suppression in such stands is substantial, it is inadequate to allow for tree crown differentiation into dominants and subordinates and the growth of such stands often stagnates (fig. 6) (Myers and Van Deusen 1960a). With this natural forest development, undoubtedly exacerbated by fire exclusion, cleaning or precommercial thinning in Black Hills ponderosa pine forests began early in the 1900s (Bates 1919).

Figure 6—Natural disturbances such as wind, wildfire, and snow are insufficient to reduce tree densities in the Black Hills to produce adequate growing conditions (e.g., light, water) for individual trees to satisfactorily develop. As a result, tree growth can stagnate and dense stands with thousands of small diameter trees can occur.

The 1906 trial compared thinned densities of 1,272 and 1,972 sapling-sized (approximately 3 inch d.b.h., 20 years old) trees per acre (TPA) to an unthinned stand containing 3,345 TPA (Bates 1919). Reporting on these trials, Bates (1919) suggested that 3,000 ponderosa pine saplings per acre utilized the full capacity of the land but 1,200 TPA assured the greatest increment per tree. He went on to say that with the exception of financial returns, the best time for thinning was when trees were in the range of 20 to 25 years of age. However, he also indicated that Black Hills ponderosa pine would respond to thinning up to 100 years of age but he suggested that the whole matter of treating older stands needed very thorough investigation. This early thinning endeavor, at least in the West, was something to conjure and far removed from the maturity of practice (Roeser 1937). There was no question in the minds of practicing foresters as to the value of thinning; there was a question as to the necessity for it. This was strongly evident as the abundance of saw timber available in the Black Hills made such investments in thinning far from necessary and its economic benefits were three or four generations away (Roeser 1937).

In 1926 the first practical application of forest thinning in the Black Hills was started near Sturgis, South Dakota (fig. 2). A 30-year-old stand with trees from 4 to 8 inches d.b.h. near the Crook Mountain Ranger Station was set aside for farmers to thin (Krueger 1936). The thinning was unsatisfactory because farmers preferred the large trees that remained and had little use for the harvested small trees (Roeser 1937). In addition to these thinning applications, thinning demonstrations were established on both the Harney and Black Hills National Forests (fig. 2). On the Black Hills National Forest, a stand containing 2,598 TPA was thinned to a density of 476 TPA and on the Harney National Forest a stand containing 2,035 TPA was thinned to 535 TPA (Krueger 1936). Using these demonstrations as an example, the Homestake Mining Company under the supervision of the Forest Service in 1931 thinned the forest around Nemo to reduce the fire hazard to protect their sawmills and infrastructure (fig. 2). This forest treatment and the other thinnings, both experimental and operational, set the stage for the establishment in 1931 of a thinning trial near Nemo. Established in a densely stocked stand with trees ranging in size from 1.0 to 5.1 inches d.b.h. and in age from 28 to 55 years, this trial tested three thinned densities compared to an unthinned control (Myers 1958; Roeser 1937).

The need for tending Black Hills forests, as exemplified by the work near Sturgis and Nemo, and the need to provide employment opportunities, did not go unrecognized by politicians. South Dakota Congressman Williamson introduced a bill in Congress to provide $150,000 for the Black Hills and Harney Forests to use for thinning and unemployment relief; however, the bill did not pass. No additional funds were provided, but in 1932 free permits were given to farmers to thin strips of the forest near Deadwood on the provision that they cut and remove all of the unmarked trees and lopped and scattered the slash (fig. 2). In addition to these public-oriented thinnings, prisoners from the Lawrence County jail also thinned trees near Deadwood to supply fuel wood to the County. These thinnings near Deadwood were designed to reduce the fire hazard around the town, provide fuel, and provide employment (Krueger 1936; Roeser 1937).

This background of official and public agreement in the practicality of forest stand improvement in the Black Hills, and a mutual desire to take advantage of all opportunities to further it, set the stage for labor that became available under the Emergency Conservation Act and National Industrial Recovery Acts of 1933. These acts established the Civilian Conservation Corps (CCC) and other relief agencies that put the unemployed to work at government expense. In 1933, approximately 285,000 to 345,000 acres of National Forest System Lands within the Black Hills were covered by small and most often young ponderosa pine trees as a result of tree regeneration following fires and timber harvesting (Roeser 1937) (fig. 7). In a large portion of these areas, the TPA averaged 3,500, tree d.b.h. averaged 3 to 4 inches, and tree heights ranged from 14 to 25 feet. A smaller portion of the area was covered by stands with pines averaging 5.5 inches in d.b.h. and 5 to 30 feet tall (Krueger 1936). The CCC program provided the workforce and there was more than enough information indicating that thinning these acres would benefit the forests. Moreover, it was a hand labor job and could not be justified financially except on a long-term basis upon which the government alone had any business to venture (Roeser 1937).

Even though thinning experiments were summarized and established in the Black Hills, there was a lack of rigorous, precise and detailed thinning rules (spacing) applicable for the CCC crews (25 to 35 men) to use. As such, different tree spacings were used depending on tree height: 1,200 TPA (6 by 6 feet) for trees 2 to 8 feet in height, 680 TPA (8 by 8 feet) for trees 8 to 15 feet in height, and 480 TPA (10 by 10 feet) for trees 15 to 30 feet in height (figs. 7, 8). In addition to thinning, trees with active mountain pine beetle (*Dendroctonus ponderosae*) attacks and trees 8 inches or less d.b.h. with western gall rust (*Endocronartium harknessii*, expressed by limb cankers) were cut (Cochran 1939; Krueger 1936; Stuart and Roeser 1944). At first, leave trees were marked but quickly it was learned that the average CC Corpsman could be taught to select leave trees with good crowns and boles and thin around the tree allowing for good crown development (fig. 9). For trees less than 2 inches d.b.h., a brush hook was used to cut the unwanted trees. For trees 3.5 inch d.b.h. and larger, a double-bit axe was used[1]. Between January 1, 1933, and December 1, 1938, the CCC thinned 237,188 acres of sapling- and pole-sized trees on national forest lands and within 9 years all of the public work programs thinned over 250,000 acres in the Black Hills (Cochran 1939; Krueger 1936; Sanders 2004; Stuart and Roser 1944). This accomplishment was noteworthy because this amount of thinning far exceeded by over a factor of 10 the number of acres that any other region of the West ever attempted to thin (Pearson 1944).

Figure 7—The Civilian Conservation Corp (CCC) thinned over 235,000 acres of ponderosa pine on the Harney and Black Hills National Forests from 1933 to 1938 (photo: Sanders 2004).

[1] Thomas Graham, who was a Civilian Conservation Corpsman stationed at Camp F1 near Mystic, South Dakota, describes thinning small ponderosa pine on a cold January day in 1934 with double-bit axes. A fellow Corpsman took his axe and was eagerly going to sink it into a large ponderosa pine pitch stump in the area where they were working. The axe on that cold day did not stick in the frozen stump as planned, but rather bounced back hitting the young man in the face.

Figure 8—The CCCs used different spacings as they thinned trees. Trees 2 to 8 feet in height were thinned to a 6-by-6 foot spacing, trees 8 to 15 feet in height were thinned to an 8-by-8 foot spacing, and large saplings 15 to 30 feet height were thinned to a 10-by-10 foot spacing (photo: Sanders 2004).

Figure 9—For cutting the large saplings, the CC Corpsmen used double bitted axes and for small saplings they used brush-hooks, with much of the work accomplished during the winter (photo: Sanders 2004).

In September, 1938, a telephone right-of-way on the Harney Forest was cleared through a stand of ponderosa pine saplings that had been thinned in 1934 by the CCCs (fig 2). The annual growth rings on several tree cross-sections were examined showing an average of 49 rings with a diameter of 3.1 inches and a cross-section area of 0.053 square feet. Forty-five rings accumulated before the thinning producing an average diameter of 2.34 inches and a cross-section area of 0.03 square feet. These results showed that the 4 years since thinning accounted for 33.5 percent of the diameter growth and 77 percent of the basal area growth of the trees thinned by the CCCs (Cochran 1939). These findings piqued managers' interest on the Harney Forest so a more rigorous sample of CCC thinning was done. Stuart and Roeser (1944) collected increment cores from trees located in random 0.2 chain (13.2 feet) wide strips transcending both thinned and unthinned stands having tree d.b.h. ranging from 1 to 10 inches. They noted that trees less than 7 inches responded to the thinning readily, but those from 7 to 10 inches in d.b.h. did not. Because 480 TPA was the lowest density used by the CCCs for trees 15 to 30 feet tall, they would easily exceed 125 square feet making this finding acceptable.

With these results, Pearson (1944) suggested that the Black Hills thinnings in these large trees were far too light. However, from this study, Stuart and Roeser (1944) recommended thinning trees less than 6 inches d.b.h. to 900 TPA to maintain self-pruning and account for damage and/or mortality resulting from animals or weather. In 1956, Myers (1958) revisited the plots that Roeser (1937) established near Nemo in 1931. Based on results from 22 to 24 growing seasons and for saw-log production, he recommended one precommercial thinning that left 550 TPA when the d.b.h. was 1 inch, 425 TPA when 2 to 3 inches, and 300 TPA when 5 inches.

In addition to these thinning experiments and evaluations of operational thinnings in the Black Hills, there were other ponderosa pine thinning trials conducted in the Western United States that informed management decisions in the Black Hills. The most applicable ones came from the Southwestern United States, such as the results of Gaines and Kotok (1954), which indicated that precommercial thinning ponderosa pine trees with d.b.h. of 3 inches or less to 600 TPA was preferred. Hornibrook (1936) and Pearson (1936) suggested thinning pole-sized (6.4 inch mean d.b.h.) ponderosa pine trees to a density of 363 TPA featuring 80 crop TPA. This thinning density provided the most increase in d.b.h. growth per tree compared to unthinned trees (Pearson 1935). Also located in the Southwest, Krauch (1949) indicated that thinning pole-sized (6.4 inch mean d.b.h.) stands leaving 60 to 90 crop TPA could shorten the rotation age of ponderosa pine by 30 years with a target tree d.b.h. of 20 inches. As a result, there was considerable information available concerning the development of ponderosa pine forests and the consensus that cleaning (precommercial thinning) small-sized (less than 8 inch d.b.h.) ponderosa pine trees was a desirable forest management objective (Harmon 1955; Pearson 1950; Smith 1962).

Forest Stand Metrics

TPA and basal area per acre (BA) by the late 1800s became standards for describing forest stand density especially when associated with stand yield. Also, quadratic mean diameter (QMD) or the diameter of the tree of mean basal area and board feet (Scribner) were used to further describe timber stands (Pinchot and Graves 1895; Stickel and Hawley 1924). However, there was also the desire to develop a stand density index that did not require a yield table and that was not affected by errors in the shape of the total BA-age curve. Reineke (1933) developed a single species even-aged stand density index (SDI) using the relationship between number of trees per acre and their average d.b.h. This index is widely used and has been modified for use in uneven-aged and mixed species stands, related to forest traits (e.g., bark beetle attacks, self-thinning, full site occupancy), and has been used to develop stand density prescriptions (e.g., planting and thinning densities) to produce desired forest conditions for a variety of uses (Long and Smith 1984; Long 1985).

Although SDI is very useful, specific instructions (marking guides) for tree selection to implement treatments most often use TPA (e.g., spacing) and BA. There is no conversion of SDI to BA because multiple BA densities are possible for any single SDI. However, BA targets are readily and quickly transferred into operation with the use of prisms, angle gages, or Relaskops™, as trees are marked to leave or cut, to produce a desired stand BA per acre (Avery 1967; Dilworth and Bell 1985). Related to SDI, and relating BA and average stand diameter, is another stand density metric, growing stock level (Myers 1967).

Growing Stock Level

While there were several thinning studies conducted prior to 1960, and many were conducted throughout the range of ponderosa pine, these studies did not provide sufficient information to prescribe intensive forest treatments or for stands with low tree densities. Also, the available studies often did not evaluate multiple thinnings nor did they allow for different product production (e.g., fiber, timber, pulp). As a result, Myers (1967) designed a study to obtain ponderosa pine growth information over a range of stand and site conditions and with minimal operational restrictions. He divided the range of ponderosa pine in the Western United States into five regions and proposed installing similar ponderosa growing stock level studies in each region to provide a comprehensive understanding and knowledge for managing ponderosa pine forests (fig. 10).

Growing stock levels (GSLs) are defined by the relationship between stand density (TPA, BA) and average stand d.b.h. GSL is the BA when the mean diameter equals 10 inches. As a result, GSL provides a target tree size (i.e., 10 inches) at a specific BA (e.g., 40, 80, 120 square feet per acre) and provides suggested tree densities for mean diameters at breast height less than 10 inches. Myers (1967) used information from Bates (1919), Harmon (1955), Myers (1958), and the 1961 Black Hills National Forest thinning guide (Myers and Boldt 1961) to estimate the residual BA that appeared best for each average stand diameter irrespective of tree age. This "best" residual BA after thinning for each diameter class considered growth per acre in cubic volume to a 4-inch top and probable length of saw-log rotations. Selected BAs were plotted over corresponding stand diameters for the Black Hills and the "best" curve showed BAs for each diameter class that would produce a mean 10 inch diameter tree and 80 square feet per acre or GSL 80 (table 1, fig. 11). Other GSL (20, 40, 60, 100, and 120) curves were drawn above and below the level 80 curve at fixed proportions. The proportions were computed from BA at a mean diameter of 10.0 inches divided by 80 (0.25 for GSL 20, 0.50 for GSL 40, 0.75 for GSL

Figure 10—The intended scope of the growing stock level (GSL) study Myers (1967) proposed included five regions of the Western United States where ponderosa pine was the dominant commercial tree species.

Table 1—Meyers (1967) used these data to determine the "best" basal area per acre for ponderosa trees to grow to a 10-inch diameter when the basal area equaled 80 square feet per acre.

Average d.b.h.	Source of recommendation: Bates (1919)	Harmon (1955)	Meyers (1958)	Black Hills guide[a]
	Trees per acre			
1	1200		550	600
2			482	600
3			416	537
4		680		412
5		555	300	318
6		435		264
7		325		200
8		220		144

[a] The 1961 Black Hills National Forest's thinning guide (Myers and Boldt 1961).

Figure 11—The initial tree densities to be evaluated in the region-wide GSL study. Meyers (1967) used data from thinning studies in the Black Hills (Bates 1919; Harmon 1955; Meyers 1958) and a Black Hills thinning guide (Myers and Boldt 1961) to establish what he called the "best" basal area for trees with different diameters and established the "best" 80 Growing Stock Level (GSL). It was defined as 80 square feet per acre contained in 10-inch diameter breast height (d.b.h.) trees (table 1).

60, 1.25 for GSL 100, and 1.5 for GSL 120) (fig. 12). Correspondingly, the desired TPA for each GSL and diameter class could then be computed (fig. 13). As a result, the BA and TPA curves for each GSL could be used to develop thinning regimes for stands with different diameters and show when future treatments would be needed to produce a desired BA and tree size. To complete the process, tree growth rates, tree sizes, and volumes produced by each GSL for the different regions of the United States where ponderosa pine was being managed were needed. The result was the ponderosa pine rangewide GSL study (figs. 10–13) (Myers 1967).

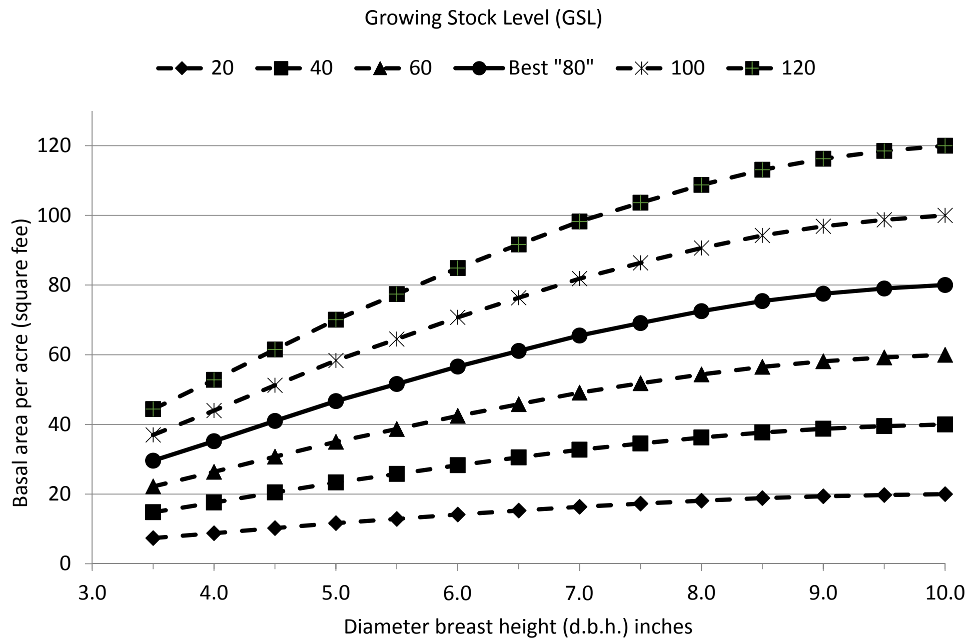


Figure 12—Using the GSL 80 (i.e., "best" basal area per acre for trees with different diameters at breast height), Meyers (1967) also added 25 percent of GSL 80, GSL 20; 50 percent, GSL 40; 75 percent, GSL 60; 125 percent, GSL 100; and 150 percent, GSL 120.

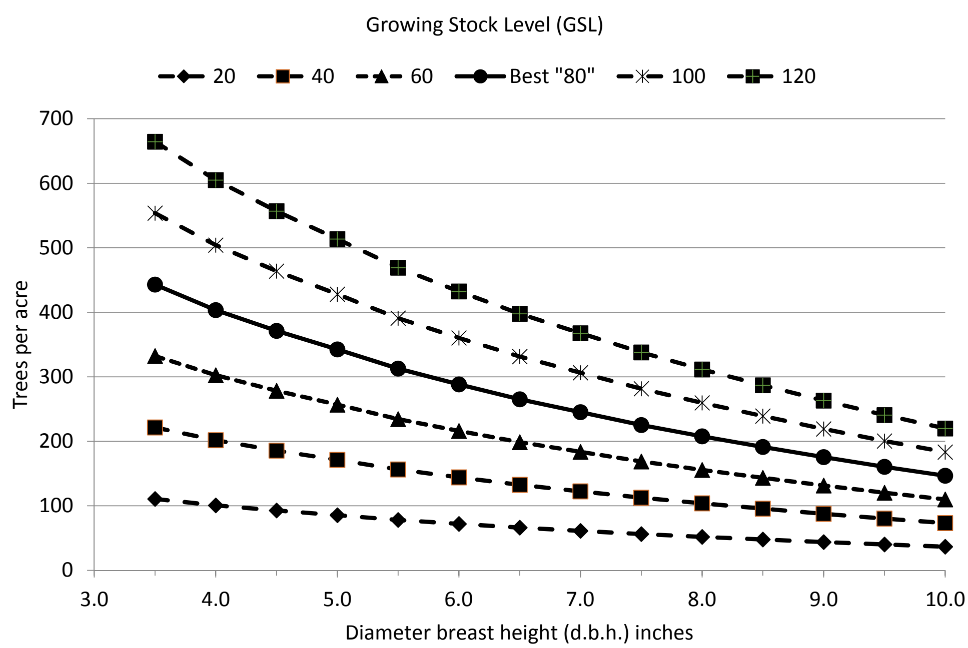


Figure 13—In addition to defining the desired basal area per acre for each GSL and d.b.h., Meyers (1967) also provided the desired trees per acre for each GSL for diameters at breast height less than 10 inches. By including more trees than desired, thinnings would be used to produce the desired number of trees when their d.b.h. was 10 inches and the target GSL was reached.

Growing Stock Levels for Black Hills Ponderosa Pine

Black Hills Experimental Forest (BHEF) elevations range from 5,600 to 5,800 feet (figs. 2, 3). Topography of the Forest is gentle with most topography flat to minimally sloping. The BHEF has a continental climate with a mean annual temperature (Rochford ≈ 5 miles to the west, 1897 to 2006) of 39.0 °F, maximum annual mean of 55.4 °F, minimum annual mean of 22.5 °F, and extreme temperatures of -47 °F and 104 °F. The mean annual precipitation is 20.1 inches with the majority falling in the spring and summer (Western Regional Climate Center 2011). The climate typically supports ponderosa pine forests and especially those where ponderosa pine is the late seral species (Meyer 1938; Oliver and Ryker 1990; Van Hooser and Keegan 1988). Soils of the BHEF 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). The habitat type is ponderosa pine-kinnikinnick (*Arctostaphylos uva-ursi*), which dominates the central Black Hills (Hoffman and Alexander 1987). These biophysical characteristics produce a forest with a 55 site index (100-year base) that falls into site quality class VI where class VII is the least productive (Meyer 1938).

In the late 1800s, mountain pine beetles and/or a fire killed a large portion of the ponderosa pine trees in the area that was to become the BHEF giving rise to a carpet of ponderosa pine regeneration with varying amounts of overstory (Boldt and Van Deusen 1974; Graham et al. 2016). Typically thousands of TPA regenerate in the Black Hills following a disturbance, but on the BHEF following these disturbances, 600 to 1,000 ponderosa pine TPA established. Using this regeneration, Myers and Boldt (1961) set out to determine (1) the maximum volume of Black Hills ponderosa pine that can be produced by sapling- and pole-sized stands on sites of average quality and (2) the maximum and minimum stand densities that will produce this potential. Therefore, the GSLs chosen to test in the Black Hills were 20, 40, 60, 80, 100, and 120.

Myers (1967) originally desired to establish different GSLs in small (0.6 to 2.0 inch d.b.h.) and large (2.1 to 4.0 inch d.b.h.) saplings and small (4.1 to 8.0 inch d.b.h.) and large (8.1 to 12.0 inch d.b.h.) poles. Within the Black Hills and on the BHEF it was difficult to locate a sufficient number of stands with similarly sized large pole trees and stands with small sapling trees in which to establish the study. In addition, the stands chosen with small saplings contained trees too limber (buggy-whips) and of insufficient tree quality to establish the study. As a result, in 1961 and 1962, 36 plots (18 in large saplings and 18 in small poles, allowing for three replications of each GSL) were located and established on BHEF (fig. 14). Both the sapling and pole plots were established in 65-year-old stands (figs. 15, 16). The sapling plots were 0.25 acres in size with 30-foot buffers around them and the pole plots were 0.50 acres in size with 45-foot buffers. To obtain maximum tree and density uniformity within each plot, square, rectangle, and parallelogram shaped plots were possible. The highest concentration of plots were located on the west side of BHEF but a few were located on the east side (fig. 17). After plot establishment, the GSLs (20, 40, 60, 80, 100, and 120) were randomly assigned to the sapling and pole plots.

Insofar as possible, dominant and codominant trees of high vigor with long full crowns and straight boles or trees that demonstrated capacity for rapid growth were chosen to leave when the plots and buffers were thinned (Myers and Boldt 1961). For each GSL, the number of residual TPA and desired BA for each class of plot (i.e., sapling or pole) were determined based on their mean d.b.h., shown in figures 12 and 13. In 1963, the thinnings and the initial tree measurements were completed (figs. 18, 19). In 1978, three unthinned sapling and three unthinned pole plots were established on the BHEF, making a total of 42 plots (table 2a,b, figs. 14, 17, 20).

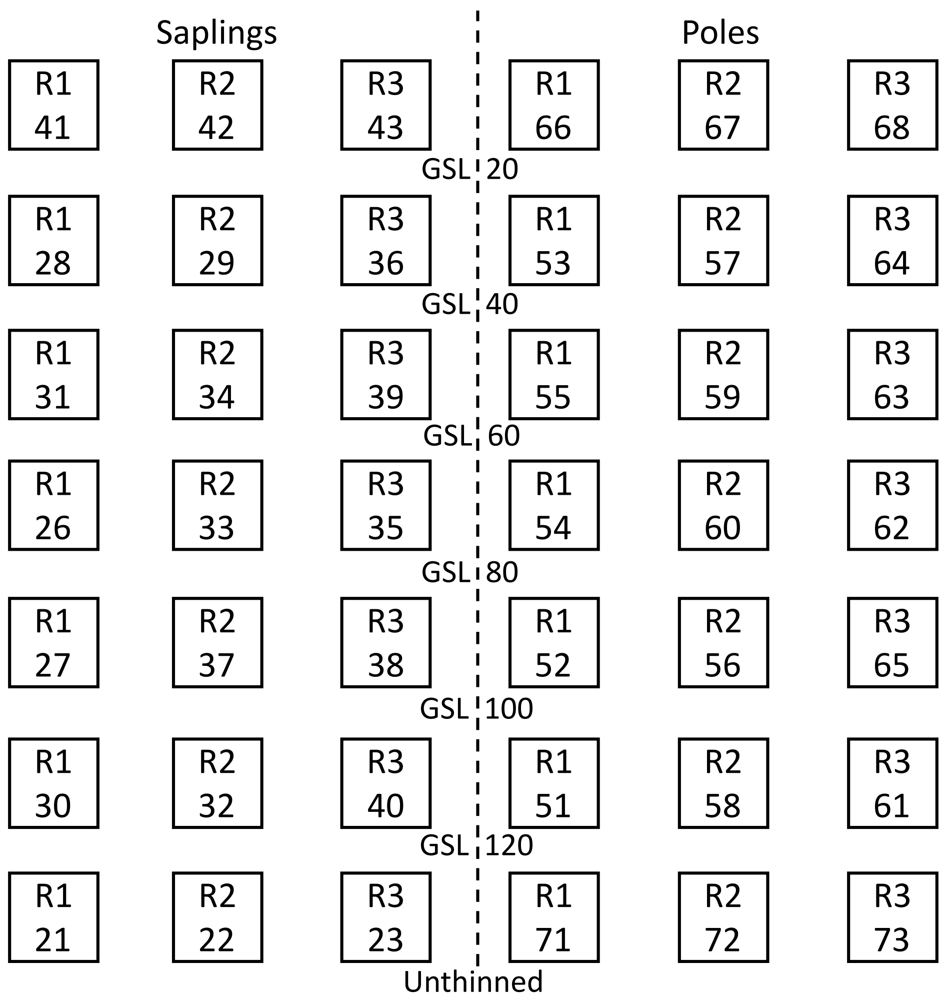


Figure 14—The growing stock levels for Black Hills ponderosa pine study were initiated in 1961 and installed on the Black Hills Experimental Forest in 1962 and 1963. Three replications of GSL 20, 40, 60, 80, 100, and 120 were established in sapling sized (3.6 to 3.8 d.b.h.) and pole sized (6.5 to 6.8 d.b.h.) stands. In 1978, three unthinned plots representative of the sapling plots and three unthinned plots representing pole-sized trees were established.

Figure 15—Similar to those that were thinned to create the sapling GSL plots on the Black Hills Experimental Forest, this 65-year-old sapling stand contained 146 square feet of basal area and 1,400 trees per acre that had a QMD of 3.3 inches (1964 photo).

Figure 16—Similar to those that were thinned to create the pole GSL plots on the Black Hills Experimental Forest, this 65-year-old pole stand contained 123 square feet of basal area and 672 trees per acre that had a QMD of 5.8 inches (1964 photo).

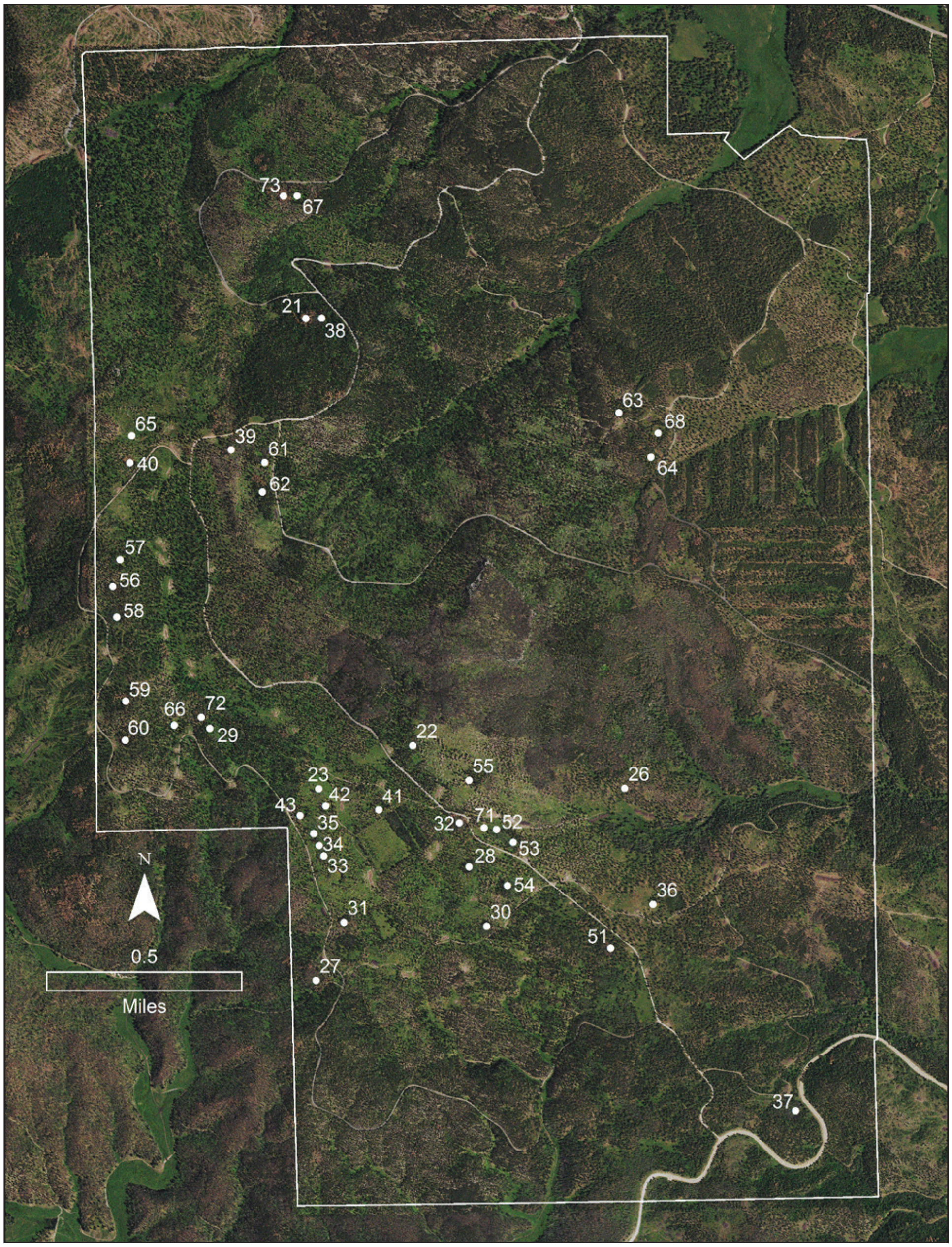


Figure 17—The 36 thinned growing stock level plots and 6 unthinned plots located on the Black Hills Experimental Forest. This depiction of the Forest was located on a 2014 National Agriculture Imagery Program (NAIP) true-color image (1 m resolution).

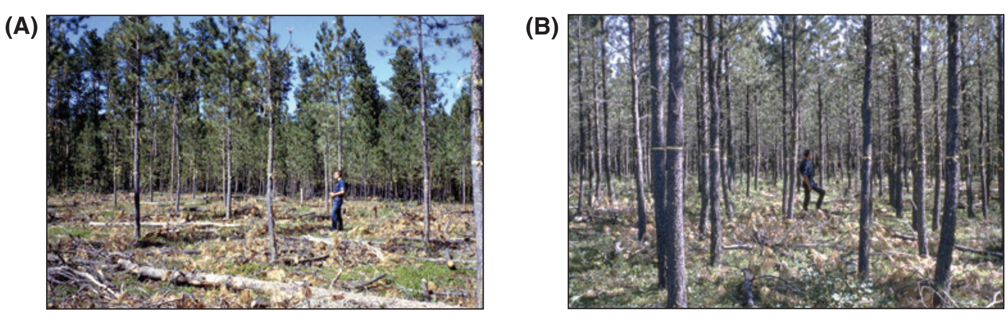


Figure 18—GSL 20 sapling plot 41 was thinned leaving 9 square feet of basal area and 108 trees per acre with a QMD of 3.9 inches (A). GSL 120 sapling plot 32 was thinned, leaving 61 square feet of basal area and 552 trees per acre with a QMD of 4.5 inches (B) (1964 photo).

(A)

(B)

Figure 19—GSL 60 pole plot 59 was thinned, leaving 43 square feet of basal area and 21 trees per acre with a QMD of 6.0 inches (A). GSL 120 pole plot 58 was thinned, leaving 88 square feet of basal area and 424 trees per acre with a QMD of 6.2 inches (B) (1964 photo).

Table 2a—Tree and stand characteristics when the sapling GSL plots were established. The GSL thinned plots were established in 1963 and the unthinned plots were established in 1978.

Plot	GSL	Trees/ ac.	Basal area ft²/ac.	SDI[a]	CCF[b]	Height feet	QMD[c] inches	Cu ft. ft³/ac.	Merch[d] Cu ft. ft³/ac.	BF[e]/ac.
Sapling GSL plots established in 1963: 65-year-old trees										
41	20	108	9	24	9	28	3.9	75	0	0
42	20	112	8	21	8	25	3.5	58	0	0
43	20	112	8	22	9	27	3.7	66	0	0
28	40	204	15	42	16	27	3.7	121	0	0
29	40	220	16	44	17	29	3.7	130	0	0
36	40	220	14	39	15	26	3.4	100	0	0
31	60	304	23	63	24	31	3.7	188	0	0
34	60	292	28	73	29	34	4.2	266	0	0
39	60	324	23	62	24	29	3.6	173	0	0
26	80	440	25	71	27	26	3.2	170	0	0
33	80	408	33	88	34	37	3.8	293	0	0
35	80	376	36	92	36	35	4.2	335	0	0
27	100	512	42	113	44	38	3.9	403	0	0
37	100	512	40	107	42	31	3.8	317	0	0
38	100	468	40	105	41	34	3.9	360	0	0
30	120	688	42	119	45	27	3.4	298	0	0
32	120	552	61	154	61	36	4.5	612	0	0
40	120	612	50	133	52	29	3.9	370	0	0
Unthinned sapling plots established in 1978: 80-year-old trees										
21	UnThin	824	160	360	146	34	6.0	3,030	1,380	6,960
22	UnThin	944	147	345	135	30	5.3	2,673	1,347	6,760
23	UnThin	808	136	315	125	32	5.6	2,587	1,167	6,000

[a] Stand density index (SDI).

[b] Crown competition factor (CCF; Krajicek et al. 1961).

[c] Quadratic mean diameter (QMD).

[d] Merchantable cubic feet.

[e] Scribner board feet.

Table 2b—Tree and stand characteristics when the pole GSL plots were established. The GSL thinned plots were established in 1963 and the unthinned plots were established in 1978.

Plot	GSL	Trees/ ac.	Basal area ft²/ ac.	SDI[a]	CCF[b]	Height feet	QMD[c] inches	Cu ft. ft³/ ac.	Merch[d] Cu ft. ft³/ac.	BF[e]/ac.
Pole GSL plots established in 1963: 65-year-old trees										
66	20	66	14	32	13	32	6.3	171	0	0
67	20	64	15	33	14	38	6.6	207	0	0
68	20	62	16	34	15	37	6.9	217	0	0
53	40	124	33	69	30	41	7.0	462	0	0
57	40	136	30	67	28	41	6.4	411	0	0
64	40	136	30	66	28	38	6.4	380	0	0
55	60	198	47	101	43	37	6.6	576	0	0
59	60	218	43	97	41	38	6.0	524	0	0
63	60	194	48	103	44	41	6.7	655	41	220
54	80	248	65	138	59	45	6.9	960	13	60
60	80	262	61	132	56	41	6.5	799	27	120
62	80	244	67	140	60	46	7.1	995	80	360
52	100	288	86	178	77	52	7.4	1,458	212	1,060
56	100	356	71	158	66	39	6.0	848	14	60
65	100	334	77	167	71	44	6.5	1,048	53	240
51	120	370	100	210	90	49	7.0	1,539	177	860
58	120	424	88	195	82	39	6.2	1,080	9	40
61	120	354	103	213	92	50	7.3	1,655	188	960
Unthinned pole plots established in 1978: 80-year-old trees										
71	UnThin	589	180	370	160	41	7.5	3,145	1,071	4,945
72	UnThin	872	167	377	156	37	5.9	2,640	524	2,760
73	UnThin	788	156	349	145	37	6.0	2,306	212	1,040

[a] Stand density index (SDI).

[b] Crown competition factor (CCF; Krajicek et al. 1961).

[c] Quadratic mean diameter (QMD).

[d] Merchantable cubic feet.

[e] Scribner board feet.

(A)

(B)

Figure 20—In 2004, the unthinned sapling plots contained many deformed and damaged trees (A: plot 22) and the unthinned pole plots were dense with many small diameter trees (B: plot 71).

The methodical plot establishment and subsequent thinning resulted in stand structures in the different GSLs very close to the hypothetical distributions Myers (1967) described. For example, Myers (1967; figs. 12, 13) suggested 8.5 to 8.8 square feet of BA and 102 to 108 TPA for 3.8 inch d.b.h. trees for GSL 20. These values were very similar to the 8 to 9 square feet of BA and 108 to 112 TPA that were established for the sapling GSL 20 (table 2a,b). The GSL 100 sapling plots had similar congruity to the desired BA of 44 square feet for 3.9 trees, and BA ranged from 40 to 42 square feet (fig. 12, table 2a,b). As the plots were measured in 1963 five sapling plots had a total of 28 TPA removed and three pole plots had a total of six TPA removed, refining the desired number of trees per acre (fig. 13).

Dead branches to about 6 feet (head height) were pruned on trees in the plots. Myers (1967) provided the thinning regime to be followed (figs. 12, 13) as the trees developed. The plots were to be measured every 5 years and, if necessary, be thinned to achieve desired TPA and BA as outlined in figures 12 and 13. This goal was readily achieved in 1968, 1973, and 1978 and sometimes trees were removed in each of these years to produce the desired stand structures (fig. 21). After 1978, the plots were not measured and thinned regularly and all GSL plots had trees removed in 1998 to achieve the desired structures (fig. 21).

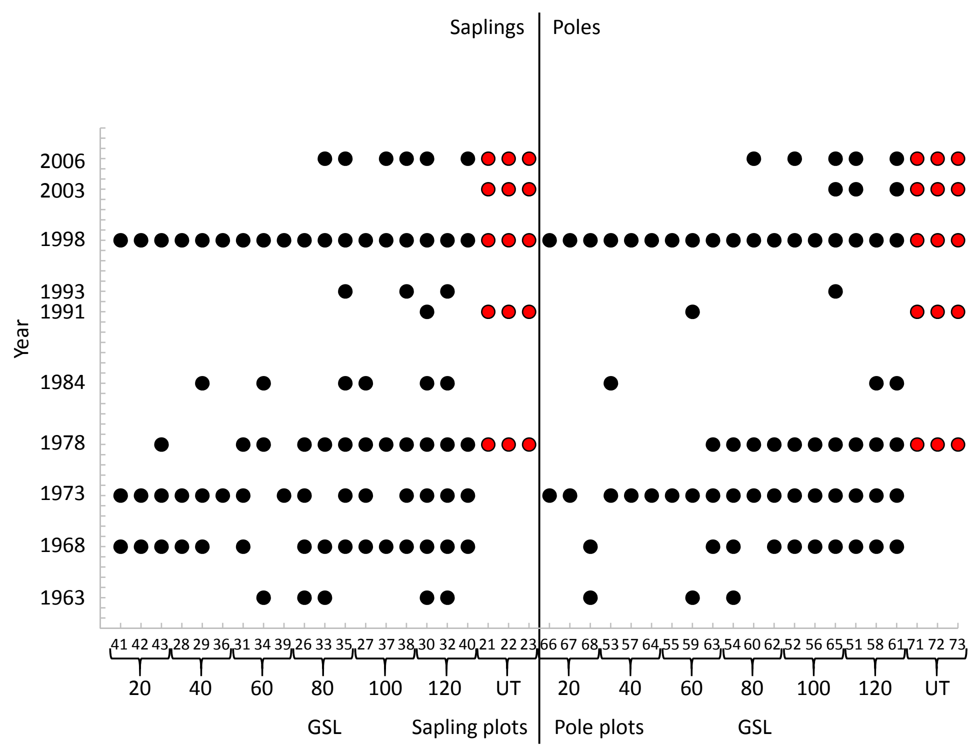


Figure 21—Trees were removed (black dots) from the plots (numbers on the x-axis) as they developed to maintain the desired trees and basal area per acre with trees removed on every plot in 1998. The red dots indicate years in which trees died on the unthinned (UT) plots.

Analysis

In the study plan, Myers and Boldt (1961) estimated large amounts of data would be collected during the course of the study and the projected study completed in 1980. Through 1978 the plots were measured and maintained as the study plan directed but after 1978 the measurement and thinnings occurred at a variety of intervals ranging from 2 to 6 years. Height and diameter measurements and thinnings when necessary continued on each of the plots through 2014 producing thousands of tree measurements. The Forest Vegetation Simulator (FVS) was used to summarize the data for each measurement and produce stand level metrics. These included: BA, TPA, stand density index (SDI), quadratic mean diameter (QMD, the diameter of the tree with the mean basal area), mean total tree height, total cubic feet volume (cubic feet per acre), merchantable cubic feet volume (cubic feet per acre, 9.0 inch d.b.h. and 6.0 inch top), and Scribner board feet per acre (table 2a,b) (Dixon 2002; Keyser and Dixon 2008; Wykoff et al. 1982). Included in these summarizations are the characteristics of trees removed and lost on each of the plots over the 52 years.

A Generalized Linear Mixed Model (GLMM) was used to analyze all responses. The predictors included GSL, pole or sapling, year, thinning, and the GSL by pole or sapling interactions. The models incorporated a log-link function to account for nonnegative response distributions. A repeated measures temporal correlation structure was incorporated into all models using a radial smoother for each plot (Ruppert et al. 2003). Treatment-level comparisons between main and interaction fixed-effect levels were adjusted using Tukey's method and determined using least squares means (Kramer 1956). Degrees of freedom were adjusted using the Kenward-Roger method (Kenward and Roger 1997). When necessary, an empirical sandwich covariance estimator was included in order to account for over dispersion (White 1982). All analyses were conducted using SAS PROC GLMMIX in Version 9.4 of the SAS System for Windows (Copyright © 2014 SAS Institute Inc.). A detailed summary of the analyses for each response variable is shown in Appendices A and B.

Results

Several publications summarizing portions of the study were completed (Alexander and Edminster 1981; Boldt 1971; Boldt and Van Deusen 1974; Boldt et al. 1983; Edminster 1988; Oliver 2005; Severson and Boldt 1977). However, a comprehensive presentation of how the ponderosa pine trees located on the GSL plots in the Black Hills developed under the different thinning regimes (GSLs) that Myers (1967) presented has not been completed. The following narratives describe how the stand and tree metrics changed over time on each of the GSLs (1963 through 2014) and unthinned plots (1978 through 2014) for both the sapling and pole plots (figs. 21, 22, 23).

As randomly assigned to plots with QMDs ranging from 2.1 to 4.0 inches, the large sapling plots were well distributed on the BHEF (fig. 17). Trees on the quarter-acre sized sapling plots ranged in QMD from 3.2 to 4.5 inches and the mean was 3.8 inches and their mean height was 30.5 feet (table 2a,b). In 1978, three unthinned sapling plots (21, 22, 23) were established and their tree's mean height was 74 feet and the QMD was 5.6 inches (table 2a,b). As prescribed by Myers (1967), the small pole 0.5 acre sized plots were to be established in stands with 4.1 to 8.0 inch QMDs. The small pole plots established by Myers and Boldt (1961) on the BHEF had QMDs ranging from 6.0 to 7.4 inches, the mean was 6.7 inches, and their mean height was 41.6 feet (table 2a,b, fig. 17). The QMD of trees in the three unthinned pole plots (plots 71, 72, 73) established in 1978 was 6.5 inches and their mean height was 38.3 feet (table 2a,b).

(A)  (B) 

Figure 22—In 2004, only a few trees remained in the GSL 20 sapling plots (A: plot 43) and the sapling GSL 120 plots had dense tree canopies with a needle covered forest floor (B: plot 40).

(A)  (B) 

Figure 23—In 2004, the GSL 60 pole plots had an open canopy with an herbaceous ground layer (A: plot 59) and the pole GSL 120 plots had closed canopies with a needle covered forest floor (B: plot 61).

Tree Density Expressed as Trees per Acre

When Myers and Boldt (1961) established the GSL plots, BA dominated their selection criteria for tree removal and retention, but tree density expressed as TPA was also used (figs. 12, 13). As such, the sapling GSL 20 plots contained a mean of 111 TPA (101 TPA desired, fig. 13) and the sapling GSL 120 plots contained a mean of 615 TPA (665 TPA desired, fig. 13). They achieved similar congruity between established and desired TPA for the GSLs 40, 60, 80, and 100 sapling plots (figs. 13, 24). The unthinned sapling plots had a mean of 859 TPA when they were established in 1978 and primarily through suppression and weather caused tree mortality, the unthinned plots in 2010 at age 112 years had a mean of 463 TPA (fig. 24).

The similarity between the desired and established TPA on the pole GSL plots was also rather good. This resemblance is related to how uniform the tree sizes were in the stands and how well Myers (1967) related d.b.h., BA, and TPA in the GSL concept. For example, 66 TPA were suggested for pole GSL 20 and 63 per acre were established and 398 TPA were desired on the GSL 120 plots and 383 occurred on the pole plots when they were established (figs. 13, 24). Essentially, from 1978 through 1998 when the plots were thinned, TPA on the GSL plots remained relatively constant as only a few trees were removed (figs. 20, 24). In 1978, the unthinned pole plots had a mean of 750 TPA when they were established and suppression and weather-caused tree mortality reduced the number of TPA to 505 by 2010 (fig. 24).

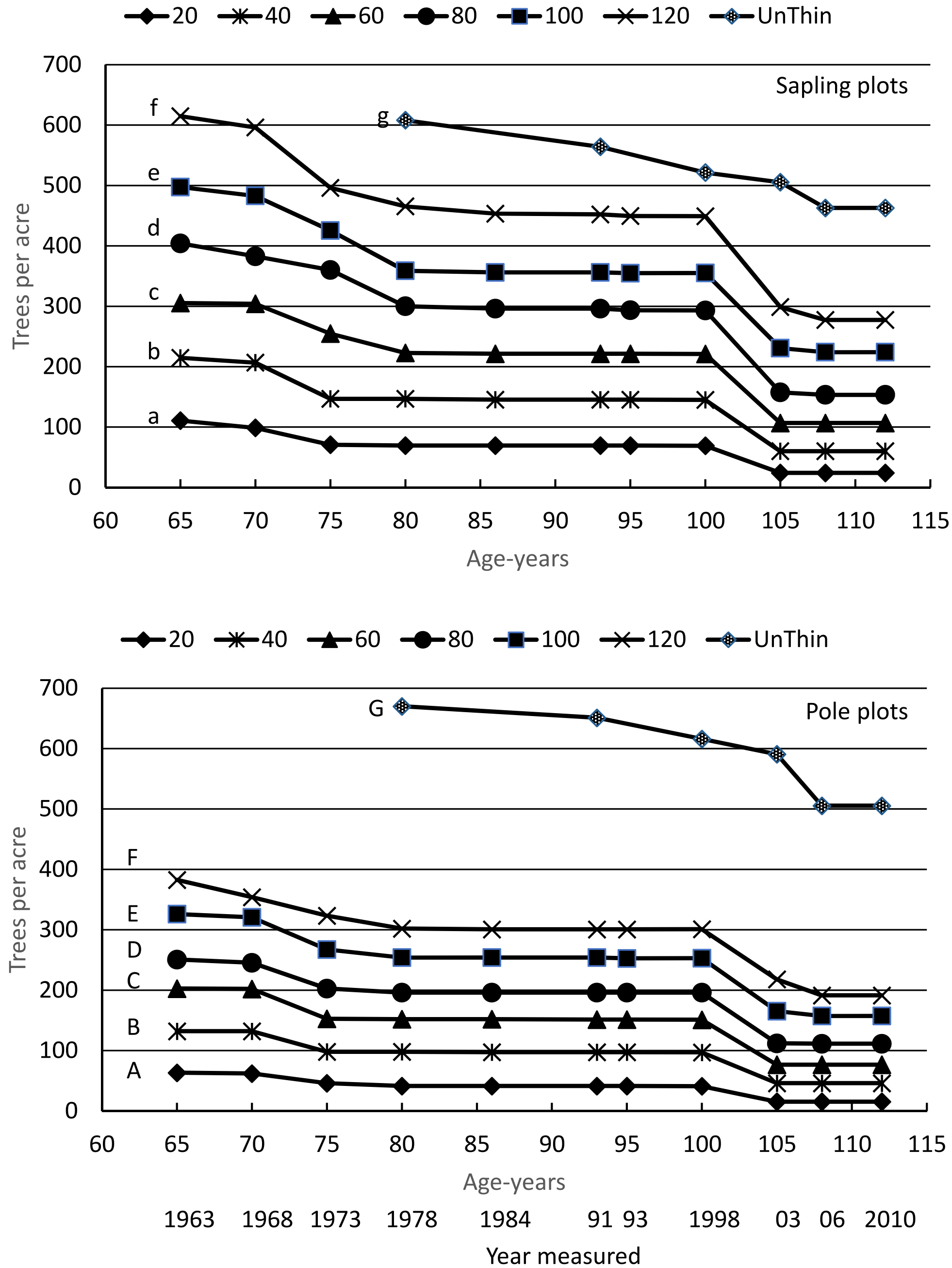


Figure 24—Mean trees per acre for each of the sapling and pole GSL from 1963 through 2010 and the unthinned plots from 1978 through 2010. A significant (alpha = 0.05) difference was detected between the number of trees per acre occurring within the sapling plots compared to the number of trees occurring within the pole plots. As a result, significant differences (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means within each plot group. See Appendix A table A1 for complete description of the analysis and Appendix B for the means and standard errors for each data point.

Over the course of the time the plots were monitored (1963 through 2010), there were significant differences between the TPA in the sapling GSL plots compared to the pole GSL plots (Appendix A table A1 sapling/pole effect probability > F < 0.0001). For example, the sapling GSL 120 plots started with a mean of 615 TPA and the pole GSL plots started with a mean of 383 TPA (fig. 24). Similarly, the pole GSL 20 plots in 2010 had a mean TPA of 15 and the sapling GSL 20 plots had a mean of 24 TPA. As a result, the TPA mean comparisons were conducted within both the sapling and pole plots (fig. 24). This finding was obvious as the QMDs of the trees in the sapling plots were smaller than those in the pole plots as prescribed by Myers (1967), so as a result the sapling plots had more TPA. This trend continued through 2010 as the TPA in the sapling plots continued to be greater than in the pole plots. In addition, the uniformity of TPA with the GSLs of each plot group was high, since no statistical (alpha = 0.05) grouping of means were detected within each respective plot type (sapling and pole). This finding is the result of all who tended these plots over the years, diligently following the prescriptions that Myers (1967) designed. The TPA in the unthinned plots also declined from 1978 through 2010 with suppression and weather being the primary mortality causes that reduced the TPA in the sapling plots from 859 to 463 and from 750 to 505 TPA in the pole plots (fig. 24).

Stand Density Index

A significant difference was found between the SDIs occurring on the sapling plots compared to those that occurred on the pole plots (Appendix A table A2, sapling/pole effect probability > F, 0.0255). Therefore, the SDI means were separated within each of the plot types (fig. 25). Having more TPA, the sapling plots had greater SDIs than the pole plots. The peak SDIs of the GSL plots occurred on the GSL 120s in 1998 when the sapling plots reached 288 and the pole plots reached 264 (fig. 25). Within the pole plots, the mean SDIs for the GSL were rather unique except for the GSL 100 and 120 plots, which had similar SDIs. In the sapling plots, the SDIs of the GSL 80 and 100 plots were similar to each other and to their adjacent GSL (i.e., 60 and 120). From establishment in 1978, the SDI for the unthinned sapling plots was relatively constant ranging from 340 to a low of 307 through 2010 (fig. 25). Similarly, the SDI of the unthinned pole plots peaked at 397 in 2003 and decreased to 327 by 2010. These SDI levels were above the SDI of 264, which is the lower limit of when self-thinning occurs, suggesting that the tree mortality that occurred was expected (fig. 25).

Basal Area per Acre

A significant difference was detected between the BA that occurred on the sapling plots compared to the BA on the pole plots using a Generalized Linear Mixed Model (Appendix A table A3, sapling/pole, probability > F, 0.022). Therefore, significant differences (alpha = 0.05) in BA among the GSLs and the unthinned plots were determined within each plot type including years 1963 through 2010 for the GSL plots and years 1978 through 2010 for the unthinned plots.

The target BAs on both sets of plots were not consistently maintained over the course of the study and BA on the GSL plots often exceeded the desired amount (figs. 12, 26). For example, the BA on pole GSL 20 plots was 28 square feet per acre in 1973 exceeding the target of 20 square feet and 45 square feet per acre in 1998 more than doubling the target BA. The BA on the sapling GSL 120 peaked at 141 square feet per acre exceeding their target of 120 square feet per acre. The greatest BA occurred on the unthinned pole plots peaking at 195 square feet in 2003 and the BA of the unthinned sapling plots peaked at 161 square feet in 2006 (fig. 26). The decrease in BA on the unthinned plots was the result of tree mortality caused by weather and suppression. In general, GSLs 100 and 120 of both the sapling and pole plots had similar BAs and the unthinned sapling plots had a similar BA from 1978 through 2010 compared to the sapling GSLs 100 and 120. In 2010, the BA of these GSL in the sapling plots ranged from 117 to 131 square feet and the BA

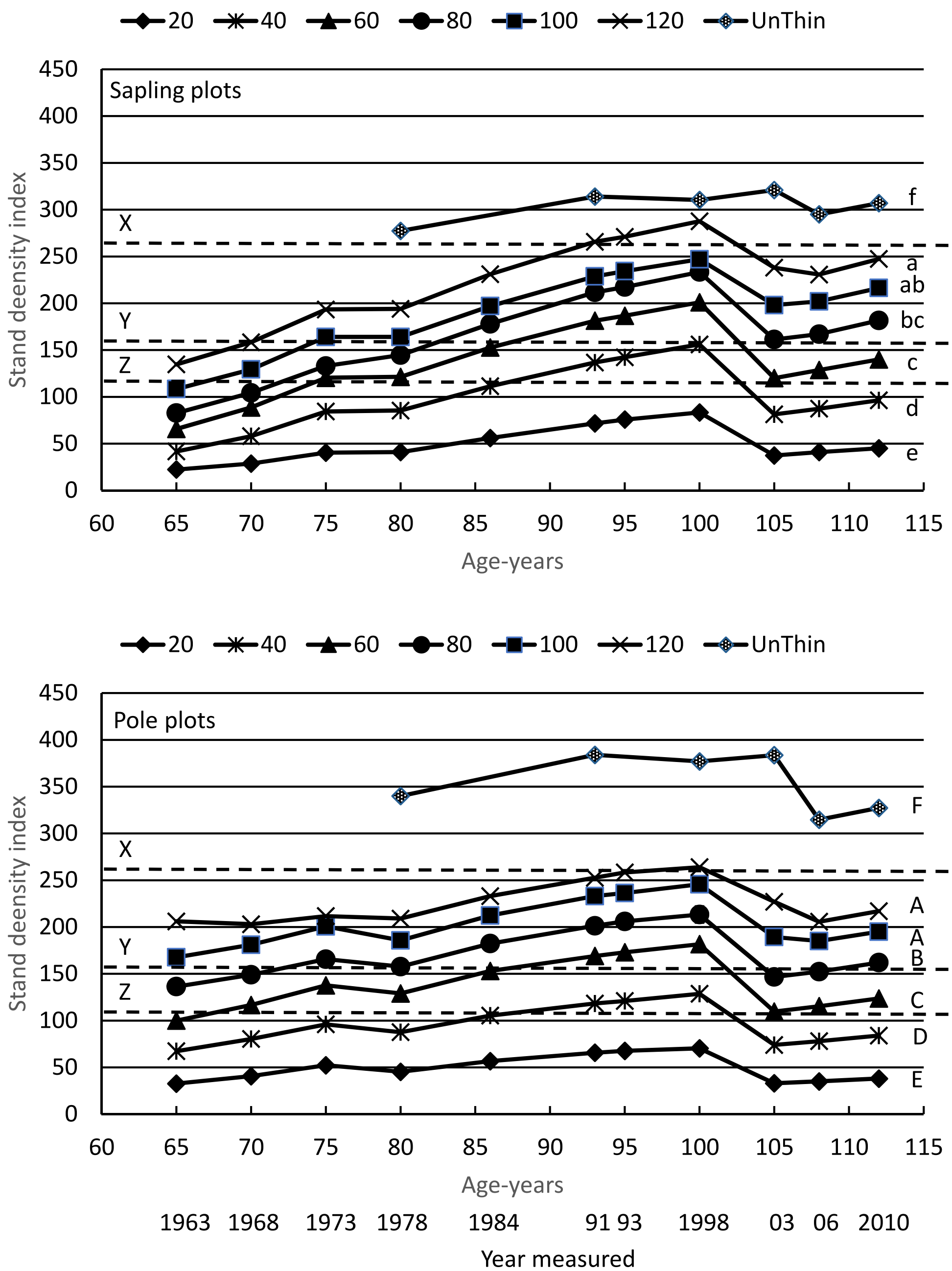


Figure 25—Stand density index (SDI) of the GSL and unthinned plots. The maximum SDI for Black Hills ponderosa pine (459) was modified from Long and Shaw's (2005) estimate of 450. Dashed line (X) is the lower limit of self-thinning (264), which ranges from 55 to 60 percent of maximum SDI and is represented by the midpoint of 57.5 percent; (Y) is the lower full occupancy (161) or 35 percent of maximum SDI, and (Z) is the onset of competition (115) or 25 percent of the maximum SDI. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A2 for complete description of the analysis and Appendix B for the means and standard errors for each data point.

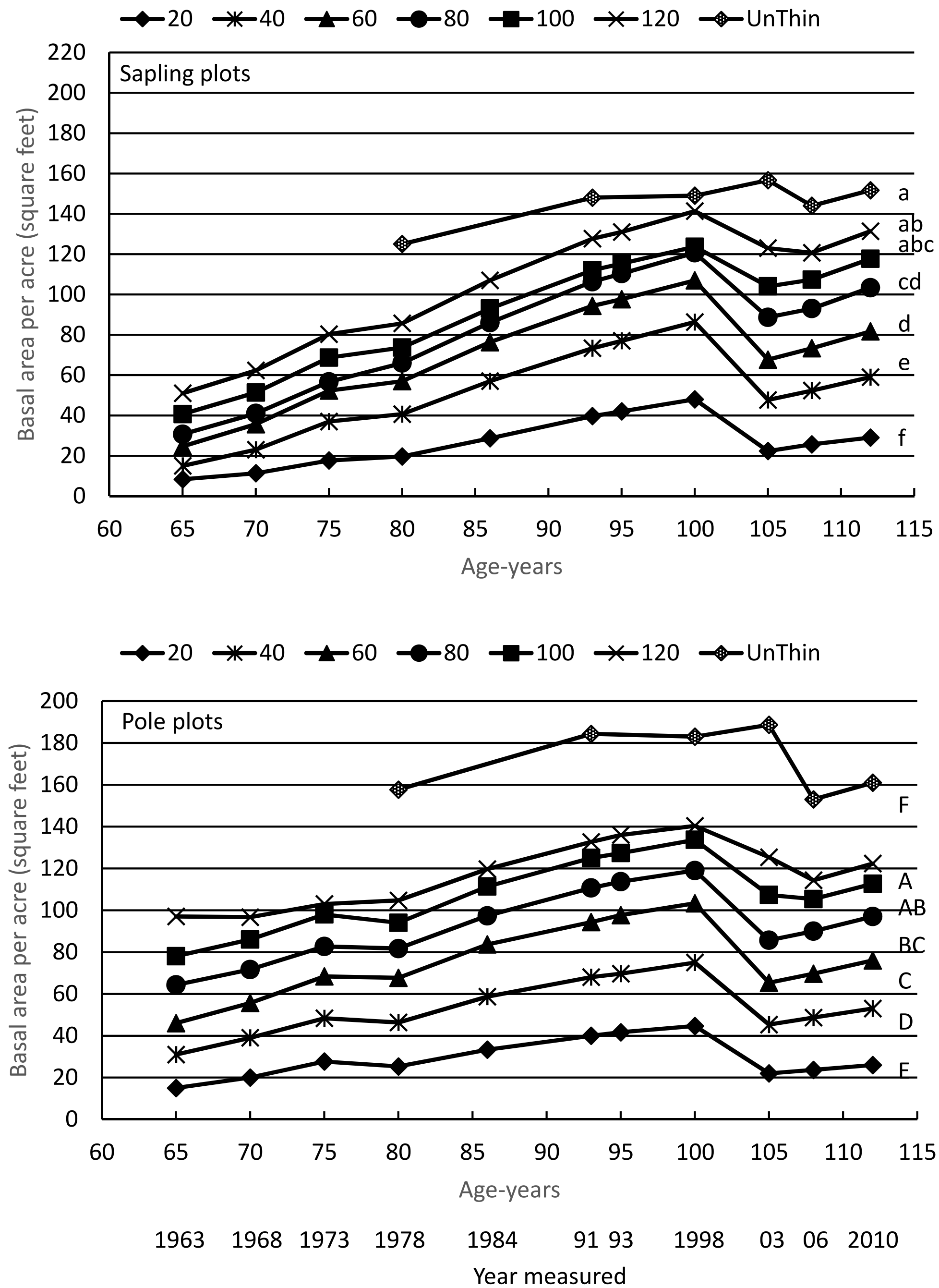


Figure 26—Mean basal area per acre for each of the sapling and pole GSL from 1963 through 2010 and the unthinned plots from 1978 through 2010. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A3 for complete description of the analysis and Appendix B for the means and standard errors for each data point.

in the same GSL in the pole plots ranged from 113 to 122 square feet. Since BA was the primary factor determining the timing and intensity of tree removal this outcome was expected, reflecting the timing and the amount of BA removed. The most BA removed on the GSL plots occurred in 1998 when the BA on all GSLs was returned to or close to their targets (i.e., 20, 40, 60, 80, 100, and 120 square feet per acre). Although not tested significantly, the slopes of the BA curves for the saplings as exemplified by GSLs 40, 100, 120 from age 80 to 100 ranged from 2.28 to 2.78 and exceeded the slopes for the same GSL curves of the pole plots with slopes ranging from 1.44 to 2.30. This observation indicates trees on the sapling plots were accumulating BA faster than those occurring on the pole plots (fig. 26).

Quadratic Mean Diameter

Trees growing on the pole plots had significantly (Appendix A table A4, sapling/pole effect, probability > F, < 0.0001) larger QMDs than those growing in the sapling plots using a Generalized Linear Mixed Model because they started nearly 3 inches larger in QMD than the trees in the sapling plots (table 2a,b, fig. 27). As a result, the QMDs were separated using Tukey-Kramer of least squares means within both the sapling and pole plots (fig. 27).

As would be expected, trees with the largest QMD occurred within the sapling plots with the lower tree densities (i.e., GSLs 20, 40, 60). However, the QMDs for sapling GSL 20 (4.0 to 15.0 inches) and 40 (4.0 to 13.4 inches) were not significantly different from each other nor were these QMDs different than the QMDs for GSL 40 (4.0 to 13.4 inches) and 60 (4.0 to 11.9 inches). In addition, the QMDs for GSL 80 (4.0 to 11.2 inches) were statistically similar to QMDs for GSL 60 (fig. 27). The trees with the smallest QMD and not similar to the QMDs occurring on the other GSL sapling plots were the trees in the unthinned sapling plots that had QMDs ranging from 5.6 inches in 1978 to 7.8 inches (fig. 27).

The pole plots were minimally thinned from 1978 through 1998 and BA accumulated on more trees than outlined for each of the GSLs (figs. 12, 13, 24, 27). When established in 1963 the QMDs on the pole plots ranged from 6.0 to 7.4 inches and the trees growing on the GSL 20 plots had the fastest QMD growth and largest QMDs beginning in 1968 through 2010 (17.7 inches) (table 2a,b, fig. 27). In addition, the QMD of trees growing on the pole GSL 20 plots was 3.2 inches greater than the QMD of trees growing on the GSL 40 plots at age 112 years. Because trees were not removed, the desired 10 inch QMD on trees in the GSL 20 sapling plots occurred in 1991 at age 93 years, in 1993 at age 95 years for trees in GSL 40, in 2000 at age 102 for trees in GSL 60, in 2003 at age 105 for trees in GSL 80, in 2010 and at age 112 years for trees in GSL 100 (QMD = 9.8 inches) (fig. 27).

Tree Growth Response to Thinning

Bates (1919) suggested that thinning of 100-year-old ponderosa pine trees needed to be investigated and in 1998 at age 100 years, all GSL plots were thinned. The sapling and pole plots significantly responded differently to the thinnings, both in terms of basal area and QMD growth (Appendix A tables A5, A6, sapling/pole probability > F, < 0.0001: BA, 0.0013: QMD). Trees in both the sapling and pole plots significantly increased their basal area (square feet per tree per year) and QMD (inches per tree per year) increment in response to the thinnings. This increase was noticeable after the thinnings (1998), the BA equaled and many times exceeded the before thinning BA even though large amounts and proportions of BA were removed in the GSL plots (fig. 26).

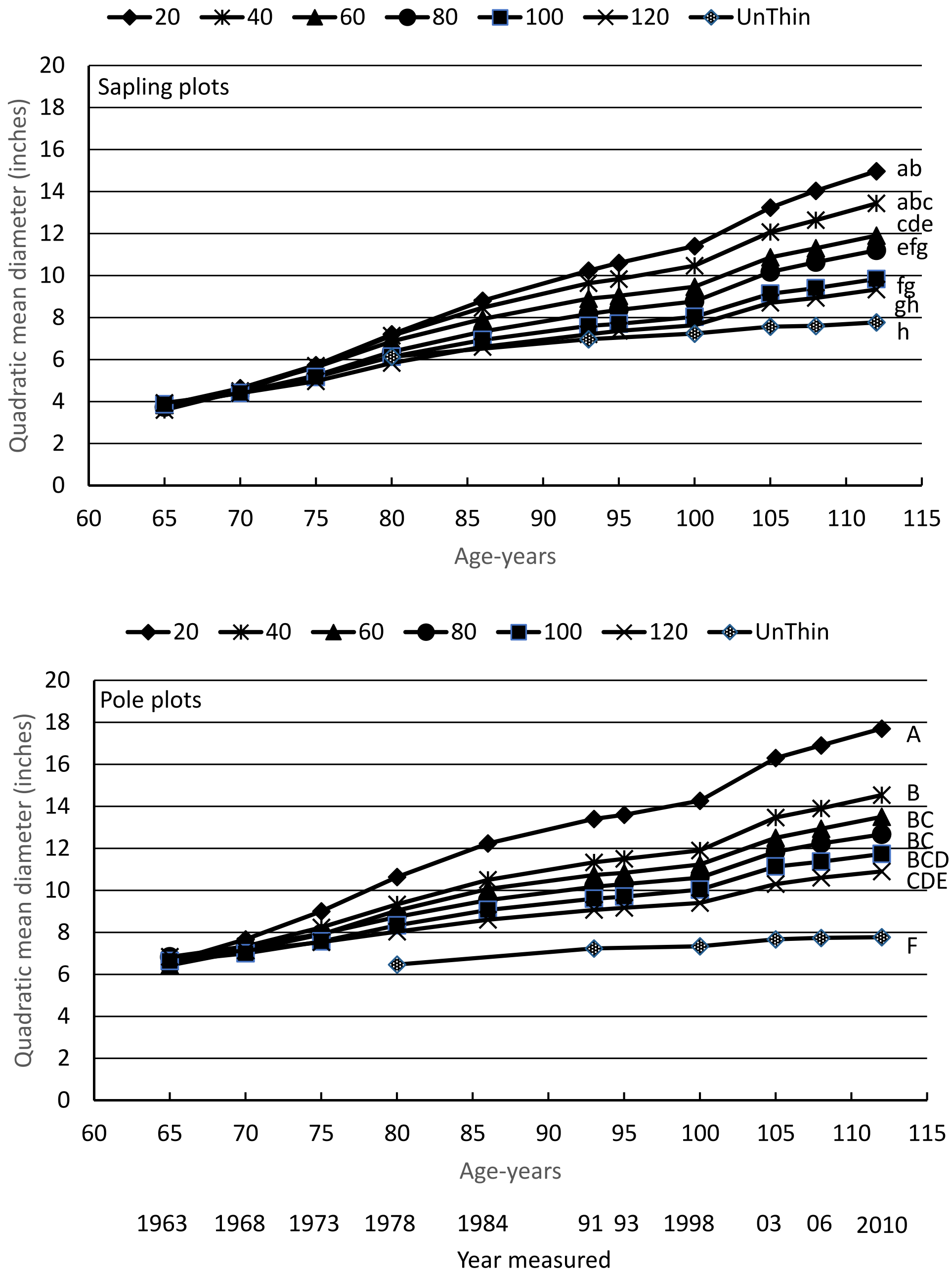


Figure 27—Quadratic mean diameter (QMD) for each of the sapling and pole GSL from 1963 through 2010 and the unthinned plots from 1978 through 2010. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A4 for complete description of the analysis and Appendix B for the means and standard errors for each data point.

For example, 23 square feet per acre (51 percent) were harvested in the thinning of the pole GSL 20, 45 square feet per acre (40 percent) in the pole GSL 40, and 22 square feet per acre (53 percent) in the thinning of sapling GSL 20 plots.

After the 1998 thinnings, in all GSLs, the change in periodic mean annual basal area increment per tree was significantly greater (age 105 through 112 years) after thinning than before (age 95 through 100 years) (fig. 28). Periodic mean annual basal area increment on trees in pole GSL 20 plots prior to thinning was 0.02 square feet per year per tree and after thinning the rate was 0.05 square feet per tree per year or a 146 percent increase (fig. 28). In addition, the post-thinning basal area increment compared to the pre-thinning rate on trees in the pole GSL 40 plots was 210 percent, 220 percent on trees in the GSL 80 plots, and nearly 200 percent (193 percent) on trees in the GSL 120 plots (fig. 28). Similar to the post-thinning increment of trees on the pole plots the significant basal area increment per tree per year on the sapling plots post-thinning ranged from 123 to 200 percent (fig. 28). Also, on both sets of plots the magnitude of the increment was greater on the low tree density plots with the greater percentage increase occurring on trees within the plots with the greater tree densities (fig. 28).

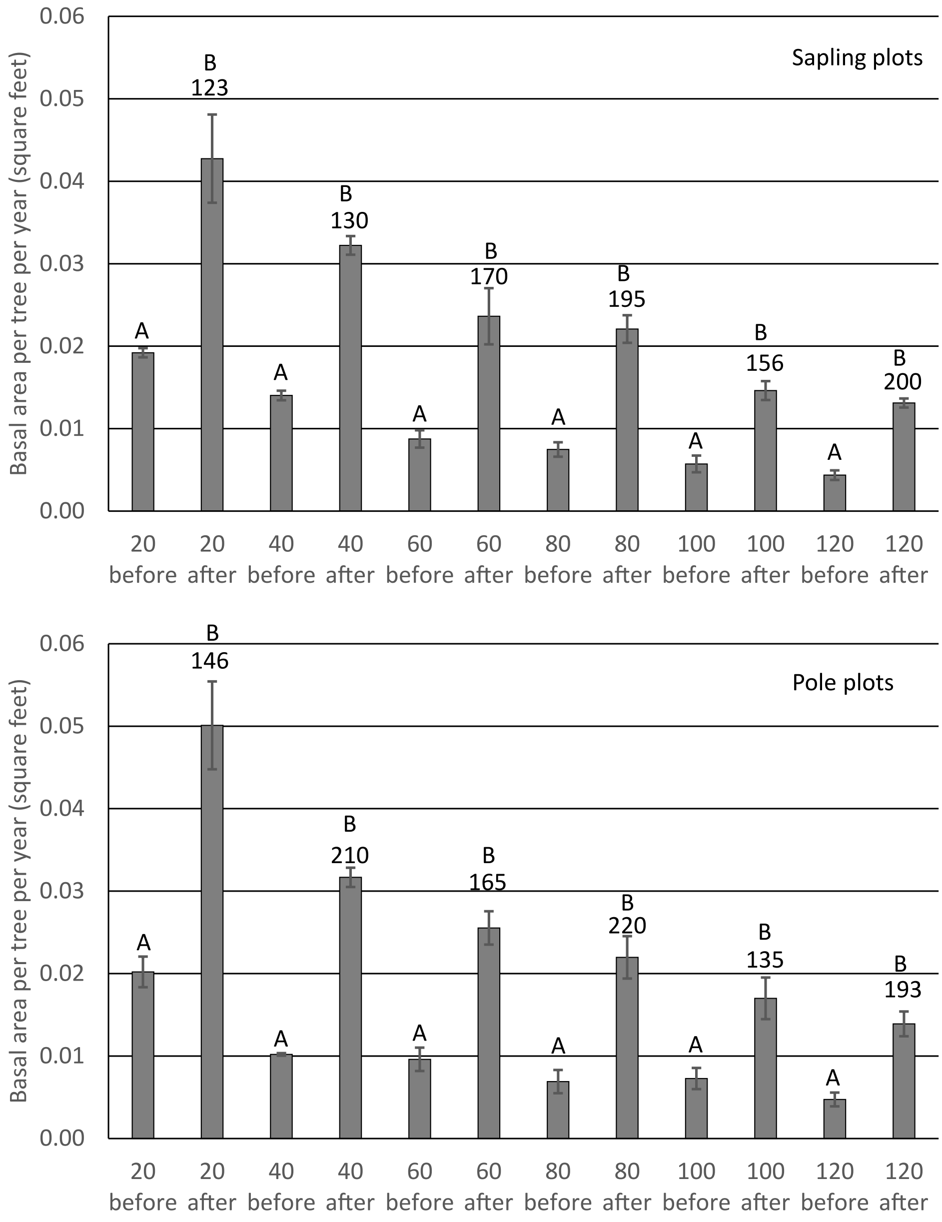


Figure 28—Periodic mean annual tree basal area increment for each GSL before (age 95 to100 years) and after the 1998 thinnings (age 105 to 112 years) within both the sapling and pole plots. Numbers above the bars indicate the percentage change in tree basal increment after the thinnings compared to the increment before the thinnings. Vertical lines are the standard error of the means. Significant (alpha = 0.05) differences between basal area increment before the 1998 thinning and after the thinning among GSL and unthinned sapling plots (different letters A, B) and within the pole plots (different letters A, B) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A5 for complete description of the analysis.

After the 1998 thinnings, trees on all of the pole GSL plots responded with greater QMD increments compared to the rates prior to the thinnings. Prior to the thinning, the periodic (age 95 to 100 years) mean annual QMD increment on trees in the pole GSL 20 plots was 0.13 inches and after the thinning (age 100 to 112 years) it was 0.29 over a 2.2 fold increase (figs. 27, 29). Compared to the pre-thinning periodic mean annual QMD increment, trees on the pole GSL 40 plots had a 174 percent increase, trees on the GSL 60 plots a 136 percent increase, trees on the GSL 80 plots a 187 percent increase, trees on the GSL 100 plots a 113 percent increase, and the periodic mean annual QMD increment increased 168 percent on the trees in the pole GSL 120 plots (fig. 29).

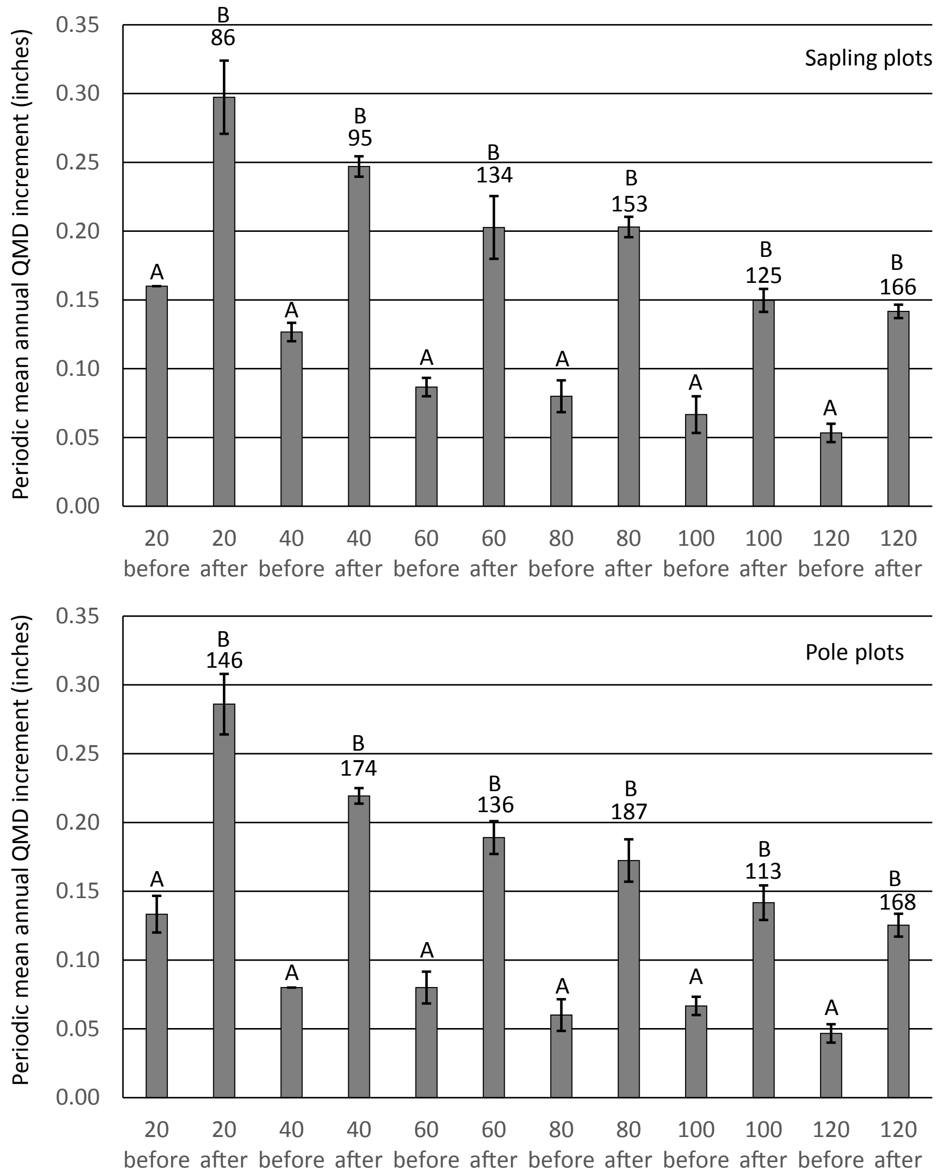


Figure 29—Periodic mean annual QMD increment for each GSL before (age 95 to 100 years) and after the 1998 thinnings (age 100 to 112 years) for both the sapling and pole plots. Numbers above the bars indicate the percentage change in QMD increment after the thinnings compared to the increment before the thinnings. Vertical lines are the standard error of the means. Significant (alpha = 0.05) differences between QMD increment before the 1998 thinning and after the thinning among GSL and unthinned sapling plots (different letters A, B) and within the pole plots (different letters A, B) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A6 for complete description of the analysis.

Most notable was the magnitude of the QMD increment on trees in the sapling GSLs 20, 40, 60, and 80 plots in response to the 1998 thinnings (fig. 29). After the 1998 thinning through 2010, the annual QMD increment on the sapling GSL 20 plots was 0.30 inches, on the GSL 40 plots 0.25 inches, on the GSL 60 plots 0.20 inches, and the annual QMD increment on the sapling GSL 80 plots was 0.20 inches. Compared to the annual QMD increment from 1993 through 1998 on the sapling GSL 20 plots there was a significant (alpha = 0.05) 86 percent increase, on the GSL 40 plots a 95 percent increase, 134 percent increase on the GSL 60 plots, a 153 percent increase on the GSL 80 plots, a 125 percent on the GSL 100 plots, and a 166 percent increase on the sapling GSL 120 plots (fig. 29).

Represented by basal area or QMD, the increment response for trees located in the sapling and pole GSL 20 occurred when stand densities were below the threshold where intra-tree competition would be expected (figs. 25, 30). Maximum stand density index (SDI) for Black Hills ponderosa pine is 459 and 25 percent or 115 of this maximum is where intra-tree competition theoretically commences (fig. 25) (Long and Shaw 2005). A maximum SDI of 83 occurred on the sapling GSL 20 plots in 1998 right before they were thinned and 5 years after the thinning the SDI was 37 and in 2010 at age 112 years it was 45 (fig. 25). Similarly, the SDI of the pole GSL 20 plots was 70 in 1998 before they were thinned and, like the trees on the sapling plots, they significantly responded with faster growth to the thinning. With these, and all SDI values that occurred from 1963 through 2010 on the GSL 20 plots being much lower than the onset of tree competition threshold, the basal area increment response to the thinning was extraordinary (figs. 25–31). The exceptional post-thinning QMD increment response of trees on the pole GSL 20 plots occurred at stand densities expressed by SDI (70) well below the level (115) where intra-tree competition would be expected (fig. 25). Similarly, the post-thinning QMD increment response of trees in the pole GSL 40 plots was also substantial, being 174 percent of the pre-thinning basal area increment (figs. 29, 31). This response occurred when the SDI was 129 only 14 points above the 115 where onset of competition would be expected (figs. 25, 29).

Figure 30—GSL 20 sapling plot 43 in 2004. In 2003, the GSL 20 plots had a mean basal area per acre of 22 feet^2, a mean of 24 trees per acre, a QMD of 13.2 inches, and an SDI of 37.

Figure 31—GSL 40 sapling plot 29 in 2004. In 2003, the GSL 40 plots had a mean basal area per acre of 48 feet^2, a mean of 60 trees per acre, a QMD of 10.5 inches, and an SDI of 81.

Achieving and Maintaining Growing Stock Levels

Myers (1967), as illustrated in figures 12 and 13, provided desired BA and TPA for each GSL to achieve a mean d.b.h. of 10 inches for a target BA (i.e., 20, 40, 60, 80, 100, and 120 square feet per acre). BA was the primary metric used for determining the number of trees that each GSL contained based on d.b.h. (figs. 12, 13). The sapling GSL 20 plots in 1963, at age 65 years, began with a mean of 8 square feet of BA and the sapling GSL 120 plots began with a mean of 51 square feet (fig. 26). These tree densities were very similar to the 8.8 square feet of BA for GSL 20 and 44 square feet for GSL 120 that Myers (1967) prescribed (fig. 12). Myers and Boldt (1961) achieved similar precision in BA targets when establishing sapling GSL plots 40, 60, 80, and 100 (figs. 12, 25). By 1978 (age 80 years) the sapling GSLs 20, 40, and 60 reached their target BAs (fig. 26). By 1984 (age 86 years) the GSL 80 sapling plots reached their target tree density and by 1991 (age 93 years) the sapling GSL plots 100 and 120 reached their target BAs. These outcomes were facilitated by tree removals in many of the plots in 1968, 1973, 1978, and 1984 (fig. 21).

For unknown reasons, but most likely administrative and logistical, from 1978 through 1998 minimal trees were removed from the sapling GSL plots (fig. 21). As a result, the BA on all GSL sapling plots exceeded their target in 1998. GSL 20 sapling plots had 48 square feet of BA, 40 plots had 86, 60 plots 107, 80 plots 121, 100 plots 124, and the GSL 120 sapling plots had 141 square feet of BA (fig. 26). In 1998, many trees were removed from the sapling GSL plots reducing their tree density to the desired BA. GSL 20 sapling plots had a mean of 45 TPA removed, GSL 40 plots 85 TPA removed, GSL 60 plots 115 TPA removed, GSL 80 plots had 136 TPA removed, GSL 100 plots had 124 TPA removed, and GSL 120 sapling plots had a mean of 151 TPA removed. As a result, in 2003 at age 105 years and 5 years after thinning, the GSL 20 sapling plots had a mean of 22 square feet of BA, GSL 40 had 48 square feet, GSL 60 had 68 square feet, GSL 80 had 89 square feet, GSL 100 had 104 square feet, and the GSL 120 sapling plots had a mean BA of 123 square feet. Again, the tree density in all of the GSL quickly exceeded their desired BA (fig. 26).

Even though the GSL 20, 40, and 60 sapling plots reached their target tree densities expressed as BA by 1978, all these GSLs had more trees than preferred (figs. 13, 24). For example, the QMD of trees on the sapling GSL 20 plots was 7.2 inches indicating the desired TPA was 38, compared to the actual mean of 69 TPA (figs. 24, 27). In 1978, the trees on the GSL 40 plots had a QMD of 7.1 inches indicating the desired TPA to be 122 compared to the 147 actual TPA and the 6.9 inch QMD of the GSL 60 plots indicated 183 TPA were preferred compared to the actual 223 (figs. 13, 24, 27). Similar to the sapling plots, the desired and installed BA for each of the pole GSLs were nearly matching (figs. 12, 26). With a desired BA of 15 square feet per acre for trees with a d.b.h. of 6.7 inches, the GSL 20 pole plots reached their target BA of 20 square feet per acre in 5 years, as did the GSL 40 plots reach their target BA of 40 square feet per acre (fig. 26). Upon reaching the desired BA of 20 square feet, the pole GSL 20 plots had 62 TPA and the desired for 7.7 inch d.b.h. trees was 56 TPA, far closer to the desired TPA than what occurred in the sapling plots (fig. 13). The pole GSL 60 plots reached their target BA at age 75 years in 1973 and the desired TPA for 7.9 inch d.b.h. trees was 156 and the actual TPA was 153. The last GSL pole plots to reach their target density was GSL 120, which occurred in 1984 at age 86 years. Tree density expressed as BA in all of the pole GSL plots exceeded their targets until the plots were thinned in 1998. Exemplifying the undesirable tree density was the GSL 20 plots exceeding their target density by year 1969 and more than doubling to 45 square feet per acre by 1998. After the GSL 20, 40, 60, and 80 plots were thinned in 1998 to or near their target densities by 2006 they all had more BA than desired (fig. 26).

In summary, the tree and stand metrics of the GSL plots generally developed as expected with the lower tree densities producing the largest QMD trees (fig. 27). However, trees in the pole plots were larger in 1963 when they were established and larger in 2010 than those growing on the sapling plots but the sapling-sized trees and pole-sized trees both changed QMDs similarly. Exemplifying this result were trees in the sapling GSL 20 plots that had a QMD in 1963 of 3.7 inches and through 1998 the QMD was 11.4 inches, increasing 7.7 inches. Trees growing on the pole GSL 20 plots in 1963 had a QMD of 6.6 inches and in 1998 their QMD was 14.3, also a 7.7 inch increase. The largest QMDs occurred on trees in the GSL 20 plots and the smallest QMDs occurred on the unthinned plots (fig. 27). The tree density expressed as BA from the time the plots were established through 2010 was very similar on the GSL 80 and 100 plots (fig. 26). A very telling outcome of how these GSL plots developed was how difficult it was to maintain the desired stand structures even experimentally on small 0.25 and 0.50 acre plots. After 1978, the GSL 20, 40, and 60 plots had more trees than desired and by age 90 all of the sapling GSL plots had more TPA than desired (figs. 12, 13, 24).

A significant difference was detected between tree height occurring on the sapling plots compared to the tree heights on the pole plots using a Generalized Linear Mixed Model (Appendix A table A7, sapling/pole effect, probability > F, < 0.0001). Significant differences (alpha = 0.05) in tree height among the GSLs and the unthinned plots were separated within each plot type including years 1963 through 2010 for the GSL plots and years 1978 through 2010 for the unthinned plots. This outcome was directly related to taller trees occurring on pole plots compared to trees on the sapling plots when they were established in 1963. When randomly established in 1963, the mean tree height on the sapling plots was 30.5 feet and the mean tree height on the pole plots was 41.6 feet (table 2a,b, fig. 32). From 1963 through 2010 no differences in tree heights were detected among the GSLs within each plot type and the mean tree height of sapling GSL was 57.0 feet in 2010 and mean tree height of the pole GSL was 61.5 feet. Of particular note, when established in 1978, mean tree height in the unthinned sapling plots (859 TPA fig. 24) was 32.0 feet and through 2010 trees growing on the unthinned sapling plots were significantly shorter than those growing on the GSL plots.

Similarly, trees in unthinned pole plots (750 TPA, fig. 24) in 1978 had a mean height of 38.3 feet and 53.1 feet in 2010 and these heights and intervening year's heights were significantly less than for trees growing on the pole GSLs (fig. 32).

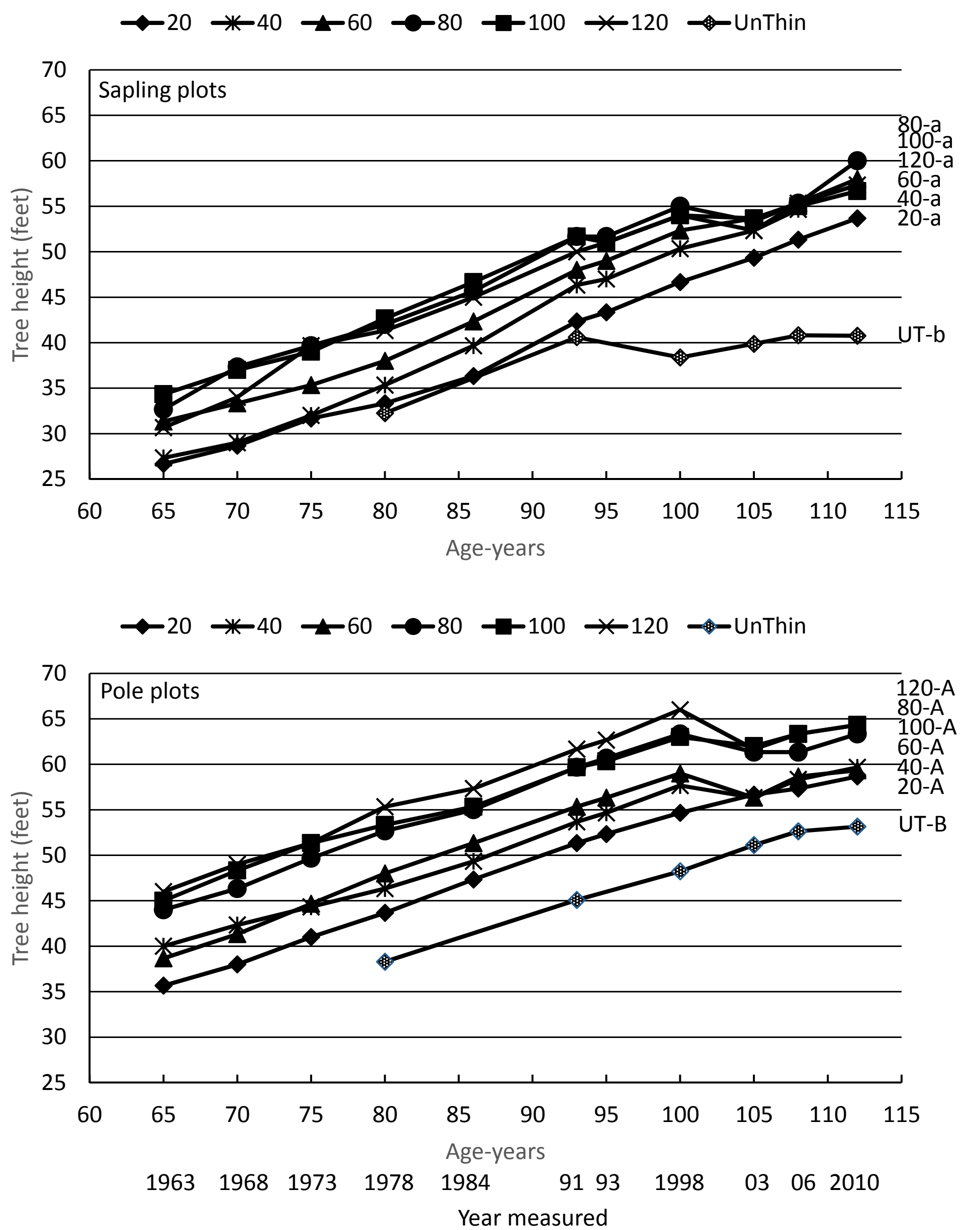


Figure 32—Mean tree heights of the sapling and pole GSL from 1963 through 2010 and the unthinned plots from 1978 through 2010. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b) and within the pole plots (different letters A, B) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A7 for complete description of the analysis and Appendix B for the means and standard errors for each data point.

After 1991 through 2010, tree mortality in the unthinned sapling plots disproportionally impacted the taller trees (fig. 32). The reduction in mean height on the GSL plots, especially the GSLs 80, 100, and 120 after 1998 was the result of needing to remove many, and sometimes tall trees, evenly throughout the plots to reduce the tree density to the desired level (figs. 12, 13).

An unforeseen finding revealed on the GSL plots was the magnitude and percentage growth response of trees growing on the GSL plots after the 1998 thinnings. Where the development of pole-sized and sapling-sized trees differ is the diverse responses observed to the 1998 thinnings. QMD increment response on trees occurring on the sapling GSL plots ranged from 86 to 166 percent and the QMD thinning response on trees in the pole plots ranged from 113 to 187 percent (fig. 29). The periodic annual QMD increment after the 1998 thinning on the sapling GSL 20 (0.16 to 0.30 inches) and sapling GSL 40 (0.13 to 0.25 inches) plots nearly doubled (figs. 29, 33). Periodic mean annual tree basal area growth did double on both the sapling GSL 20 (0.019 to 0.043 square feet) and 40 (0.014 to 0.032 square feet) plots (fig. 28). The growth response to the thinnings estimated by basal area ranged from 135 to 220 percent on trees in the pole GSL plots and 123 to 200 percent on trees in the GSL sapling plots (figs. 28, 34). These growth responses to the thinnings were most notable on trees in the GSL 20 plots as the SDI of the sapling GSL 20 was 83 and for the pole plots the SDI was 70. These SDIs are below where intra-tree competition (SDI 115) is thought to impact tree growth. Measured either by basal area or QMD, the trees in all of the different tree densities represented by the different GSLs significantly increased diameter growth rates in response to the 1998 thinnings at age 100 years validating an observation of Bates in 1919.

As planned by Myers (1967) and executed by Myers and Boldt (1961), the GSL concept can be readily described but its implementation is difficult even on the 0.25-acre sized sapling plots and 0.50-acre sized pole plots. Within 5 years after the pole GSL 20 plots were established, the target BA of 20 square feet per acre was reached.

Figure 33—GSL 20 pole plot 68 in 2004. In 2003, the GSL 20 plots had a mean basal area per acre of 22 feet^2, a mean of 15 trees per acre a QMD of 16.3 inches, and an SDI of 33.

Figure 34—GSL 40 pole plot 64 in 2004. In 2003, the GSL 40 plots had a mean basal area per acre of 45 feet[2], a mean of 77 trees per acre, a QMD of 13.5 inches, and an SDI of 74.

The exact reasons why the target densities were not maintained are unknown but such difficulty shows how challenging it would be to implement the GSL concept at stand and landscape levels. Rather than evaluating the true GSL concept, both the sapling and pole GSL plots represent different thinning regimes that illustrate how different ponderosa pine stand structures develop. In addition, a major finding Myers (1967) stressed in his GSL project was to show the different volumes the GSL would produce.

Volumes

Climate and soils determine the capacity of a site to produce forests (Barnes et al. 1998). Soils are important, but precipitation and its timing are major determinants of ponderosa pine site quality (Meyer 1938). In turn, site quality governs the amount of biomass that can be produced on a given site and, in terms of trees, cubic volume best reflects a site's inherent productive capacity (Meyer 1938). There is no record of the volume removed when the plots were established in 1963 and only the unthinned plots can be used to infer what the volumes would have been when the plots were established and the volume subsequently produced. After establishment, the amount of material removed over the course of the study can be added to the volume produced by the plots to show the total gross yield of the different GSL. But as mentioned before, these plots represent different thinning regimes rather than a strict testing of the GSL concept Myers (1967) proposed.

A significant difference was detected between the cubic feet volume per acre occurring on the sapling plots compared to the volume on the pole plots using a Generalized Linear Mixed Model (Appendix A table A8, sapling/pole effect, probability > F, < 0.0001). Therefore, significant differences (alpha = 0.05) in cubic feet volume among the GSL and the unthinned plots were separated within each plot type including years 1963 through 2010 for the GSL plots and years 1978 through 2010 for the unthinned plots when they were included.

When established in 1978, the unthinned sapling plots had a mean of 2,763 cubic feet per acre and the volume peaked in 2003 at age 108 years with 3,564 cubic feet per acre (fig. 35). In 2010, at age 112 years, the unthinned sapling plots contained a mean of 3,367 cubic feet per acre and a mean of 463 TPA (figs. 24, 35). The unthinned pole plots in 1978 had 2,697 cubic feet per acre and at age 108 years in 2006 the mean cubic volume peaked at 4,365 cubic feet per acre (fig. 35). Similar to the volumes produced on the unthinned sapling plots, the volume of the unthinned pole plots was similar to that produced on the pole GSL 120 plots. The cubic volume in the unthinned pole plots decreased to a mean of 3,642 cubic feet per acre packaged in 505 TPA by 2010 (figs. 24, 35). These cubic volumes readily represent those presented by Meyer (1938) that were 3,400 to 3,900 cubic feet per acre for 100-year-old even-aged stands growing on sites with indexes of 50 to 60.

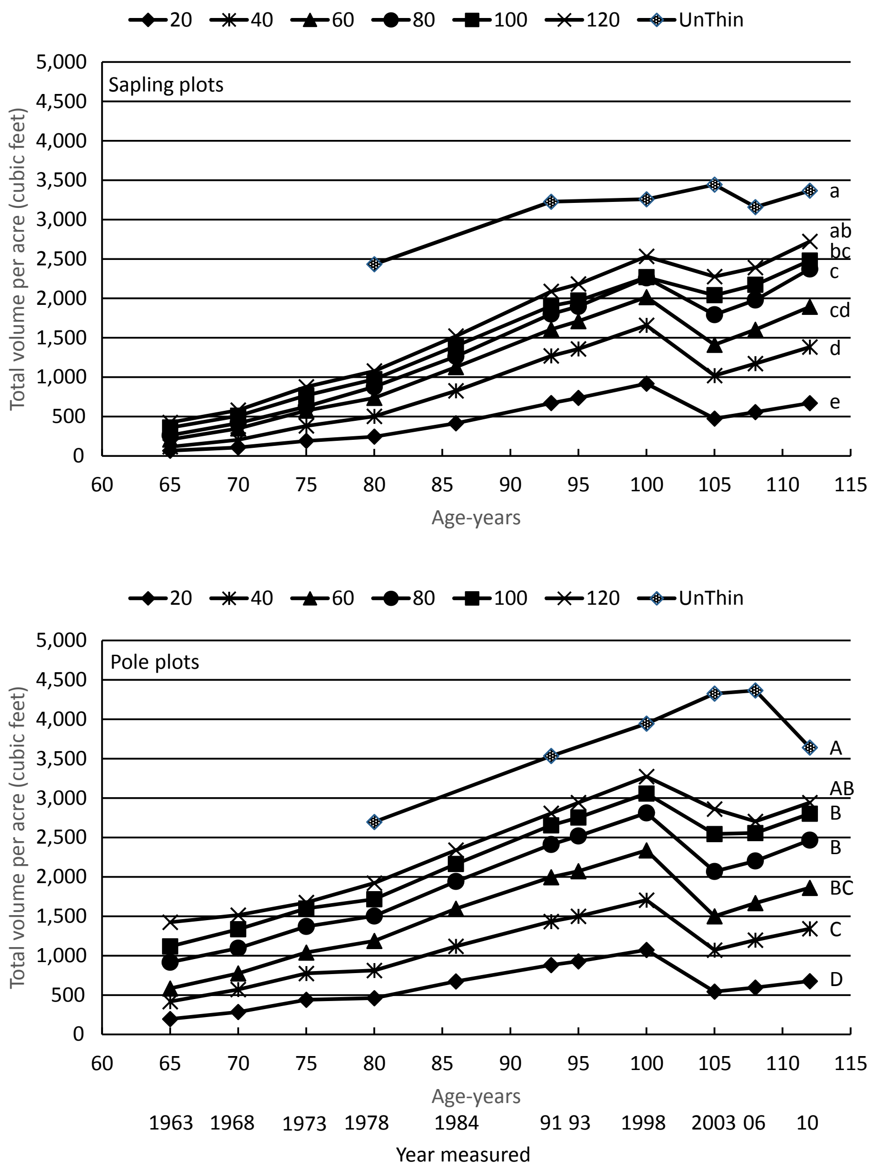


Figure 35—Total cubic feet mean volume per acre for each of the sapling and pole GSL from 1963 through 2010 and the unthinned plots from 1978 through 2010. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined within each plot type using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A8 for complete description of the analysis and Appendix B for the means and standard errors for each data point.

Similarly, Long and Shaw (2005) suggested that 2,000 to 2,500 cubic feet per acre for sites with same indexes when their SDIs neared a maximum of 450. However, the sapling unthinned plots had an SDI of 340 when they were established and 326 in 2003 when the cubic volume peaked (figs. 25, 35). The SDI of the unthinned pole-sized plots was 397 at age 105 years when their cubic volume peaked (figs. 25, 35). Although representative, these total cubic volumes on the unthinned stands and those of Meyer (1938) and Long and Shaw (2005) show the varieties of volumes that can be expected on similar ponderosa pine sites elsewhere. Even though the volumes on the unthinned sites are representative of what sites such as these could produce, these volumes were packaged in many small trees. When the volumes peaked on the sapling plots in 2003 the QMD was 7.5 inches, the BA was 158 square feet, and the TPA was 521. The trees (616 per acre) growing on the unthinned pole plots in 2003 were only slightly larger with a QMD of 7.7 inches and the BA was 195 square feet (figs. 24, 26, 27, 35).

As demonstrated by the unthinned sapling plots, mean cubic per acre wood volume was the greatest on plots that contained the most mean trees per acre and, as TPA decreased, so did the mean cubic volumes. For example, in 2010 the sapling GSL 120 plots (277 TPA) contained a mean of 2,722 cubic feet per acre, GSL 100 (224 TPA) 2,479, GSL 80 (153 TPA) 2,372, and the sapling GSL 20 (24 TPA) plots contained a mean volume of 670 cubic feet per acre (figs. 24, 35). Even though the volume decreased as the BA and TPA decreased on the GSL plots, the cubic feet volumes per acre were generally statistically similar for GSL 60 through 120. Also, cubic volumes decreased as TPA decreased on the pole GSL plots, but the volumes were greater for a given GSL than those that occurred on the sapling plots. Similar to the cubic volumes on the sapling plots, minimal statistical differences occurred among the GSL 60 through 120 (fig. 35). In 2010, when the trees were 112 years old, the pole GSL 20 plots contained a volume mean of 677 cubic feet per acre which was smaller than all of the volumes on the other pole GSL (fig. 35).

Contrary to including all years in the Generalized Linear Mixed Model for merchantable cubic feet, the analysis was confined to the years 1978 through 2010. By doing so, the years 1963 through 1973, which had minimal merchantable volume and often none, did not confound the analysis. The Black Hills variant of FVS computed merchantable volume of trees with a minimum 9-inch QMD and to a 6-inch top. A significant difference in merchantable cubic feet volume was detected between the pole plots and the sapling plots (Appendix A table A9, sapling/pole effect, probability > F, < 0.0001). Therefore, Tukey-Kramer grouping of least squares means occurred within the sapling plots and within the pole plots (fig. 36).

Interestingly, with the FVS definition of merchantable volume, the largest amount of volume in the sapling plots occurred in the unthinned plots (represented by year 2010, 1,962 cubic feet per acre) and the GSL 80 plots (represented by year 2010, 1,957 cubic feet per acre) (fig. 36). No differences in merchantable cubic feet volume were detected among the sapling GSLs 60, 120, 100, and 40, even though the 2010 volumes ranged from 1,957 cubic feet per acre to 1,188 cubic feet per acre. This finding is the result of the large amount of variation in mean volumes that occurred within each GSL from 1978 through 2010. As indicated by the significantly larger amounts of volume occurring on the pole plots, all of the pole GSL tended to have more merchantable volume than their sapling counterparts (fig. 36). Two distinct GSL volume groups (i.e., 120, 100, and 80 and 60, unthinned, and 40) occurred on the pole plots. In 2010, the GSL 120 plots had 2,345 cubic feet per acre, GSL 100 plots 2,311 cubic feet per acre and the pole GSL 80 plots in 2010 had 2,134 cubic feet per acre of merchantable cubic volume (fig. 36). Significantly, the least amount of merchantable cubic feet volume in the pole plots occurred in the GSL 20 plots and in 2010 these plots contained 609 cubic feet per acre (fig. 36).

Similar to the merchantable cubic volumes, a difference in Scribner mean board feet volume per acre occurring on the sapling plots compared to the pole plots was detected (Appendix A table A10, sapling/pole effect, probability > F, < 0.0001). Therefore, Tukey-Kramer grouping of least squares means occurred within the sapling plots and within the pole plots (fig. 37). The ordering of the GSL and unthinned plots using merchantable cubic volume or board foot volume were

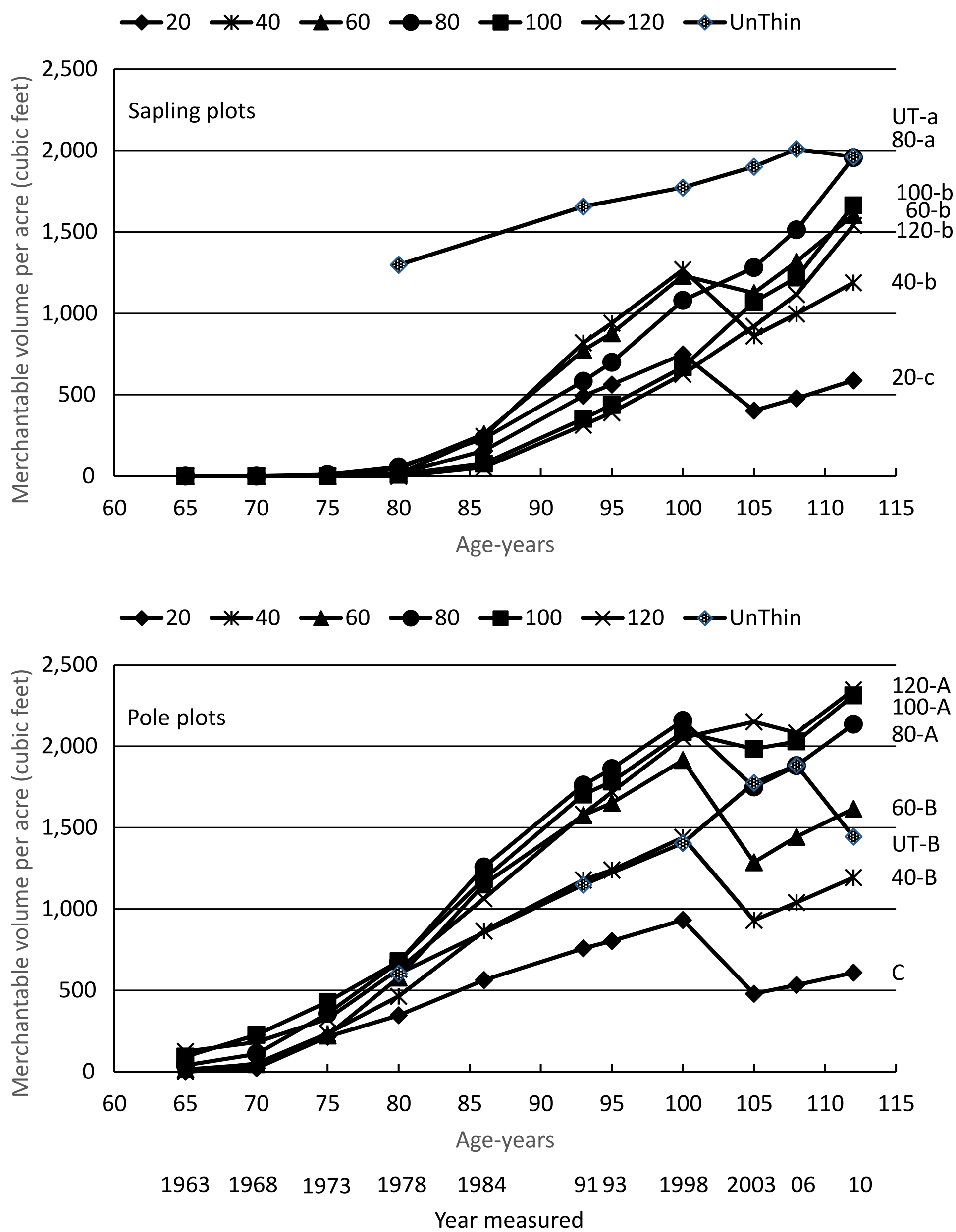


Figure 36—Merchantable (9 inch d.b.h., 6-inch top) cubic feet mean volume per acre for each of the sapling and pole GSL and unthinned plots from 1978 through 2010. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A9 for complete description of the analysis and Appendix B for the means and standard errors for each data point.

the same (figs. 36, 37). In addition, the grouping of the means for both kinds of merchantable volumes was identical for the sapling and pole plots. The largest board feet volumes in 2010 occurred on the pole GSL 120 with 11,333 board feet per acre with similar volumes occurring on pole GSL 100 and 80 (fig. 37). The largest sapling plot board feet volume in 2010 occurred on the unthinned plots with 10,053 board feet per acre and was similar to the 9,107 board feet per acre that occurred on the sapling GSL 80 plots (fig. 37). The least amount of board feet volume in both types of plots occurred on the GSL 20 plots with 3,147 board feet per acre occurring on the pole plots and 2,840 board feet per acre occurring on the sapling plots (fig. 37).

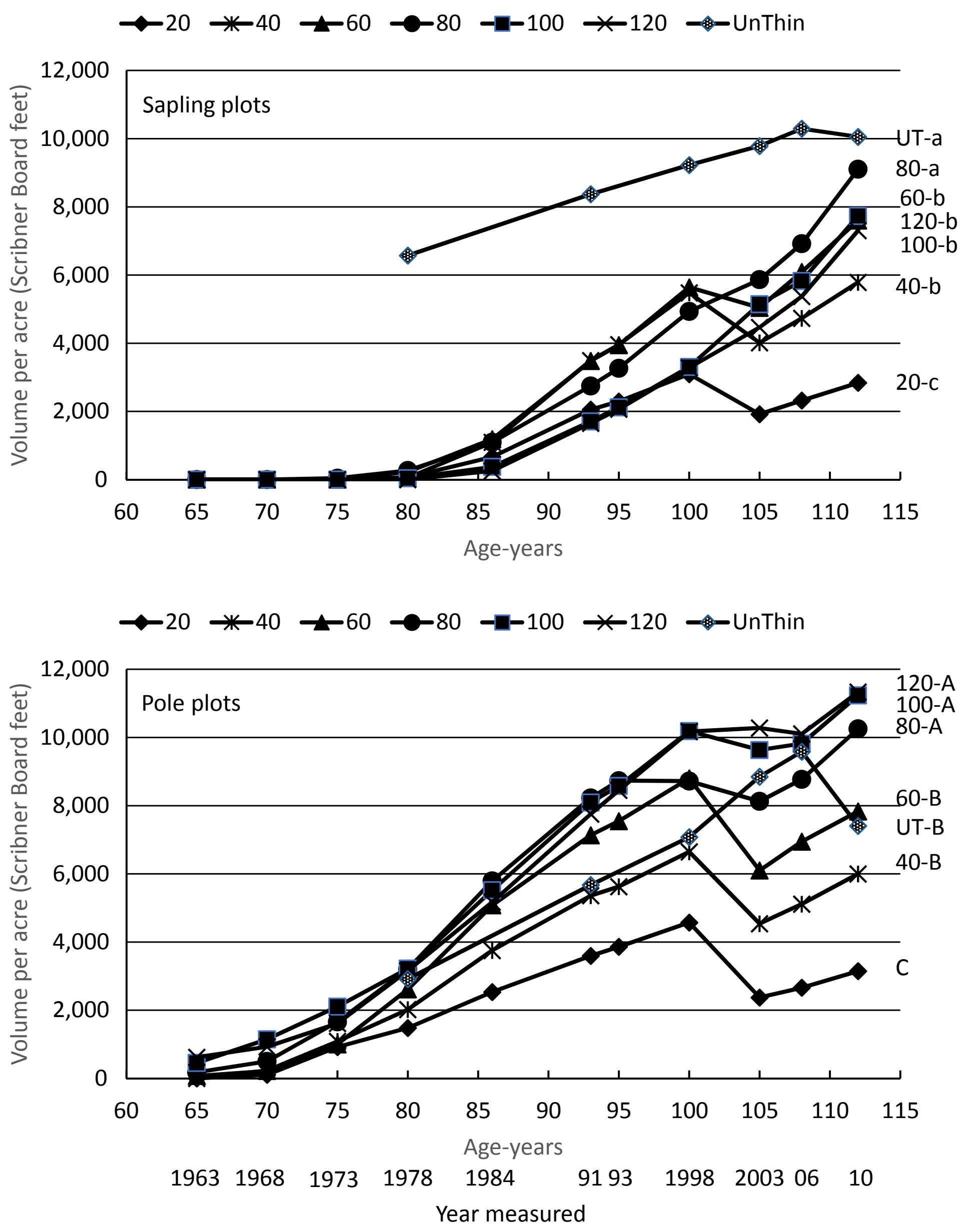


Figure 37—Scribner mean board feet volume per acre for each of the sapling and pole GSL and unthinned plots from 1978 through 2010. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A10 for complete description of the analysis and Appendix B for the means and standard errors for each data point.

Expressed as cubic feet per acre, the largest volumes were produced on sites that were not thinned in both the pole-sized and sapling-sized trees (fig. 35, year 2006, age 108 years). These volumes occurred on trees with a QMD of 7.8 inches that are marginally merchantable (fig. 27). As mentioned earlier, FVS considers trees with diameters at breast height greater than 9 inches to a 6-inch top merchantable. Therefore, the balance between QMD and volume production indicated by the GSL plots is stands with 9 to 13 inch QMDs producing 10,000 to 11,000 board feet or 2,000 to 2,300 merchantable cubic feet per acre (figs. 36, 37). Such stand metrics are typified in the GSL 80 plots most often. However, these volumes were achieved when the GSL 80 through 120 exceeded their target BA (fig. 26). Also, all of the GSL plots do not represent the GSL concept but rather depict a thinning regime that produced the particular volumes.

Volume Yield

Myers (1967) developed the GSL concept assuming multiple thinnings would occur in each GSL over time, but from 1963 through 2006, trees were removed from the GSL plots (fig. 20). As an example, his "best" GSL 80 started with 443, 3.5-inch QMD trees and the target number of 10-inch QMD trees producing 80 square feet of BA was 147 TPA (figs. 12, 13). The trees removed in the thinnings, along with the standing trees, in this case in 2010, together determine the total yield of each GSL or thinning regime. Because the sapling plots started with more trees, significantly more trees were removed from these plots than the pole plots (Appendix A table A11, fig. 38). Similarly, the GSL that started with more trees in each plot type had more trees removed. For example, the sapling GSL 120 plots had a mean of 340 TPA removed and the pole GSL120 plots had 191 TPA removed. The sapling GSL 20 plots had a mean of 87 TPA removed and the pole GSL plots had a mean of 44 TPA removed (fig. 38). Three-hundred and forty-eight TPA died in the unthinned sapling plots from 1978 through 2010 and 244 TPA died in the unthinned pole plots. Although not significant, these trees killed in both plot types exceeded those removed in the GSL thinnings (fig. 38).

Even though more trees were removed from the sapling plots compared to the pole plots, significantly more cubic volume was removed from the pole plots compared to the sapling plots (Appendix A table A12, fig. 39). The pole GSL 120 plots had 1,284 cubic feet per acre removed but this amount was not significantly different from the amounts removed (645 to 938 cubic feet per acre) from the pole GSL 40, 60, 80, and 100 plots (fig. 39). There were no significant differences among the cubic volume (386 to 671 cubic feet per acre) removed from all of the sapling GSL 20, 40, 60, 80, 100, and 120 plots (fig. 39). In addition, in the unthinned sapling and pole plots, the amount of volume lost from suppression and weather was similar to the volume removed from the GSL plots with the exception of the volume removed from the pole GSL 20 plots (fig. 39). These similar amounts in volume removed from the GSL plots, even though there was considerable difference in the means, were related to the large amount of variation in the amount of volume removed from each of the plots (fig. 39). The trees removed, and the volume contained in them, add to the total volume yield of the different GSL.

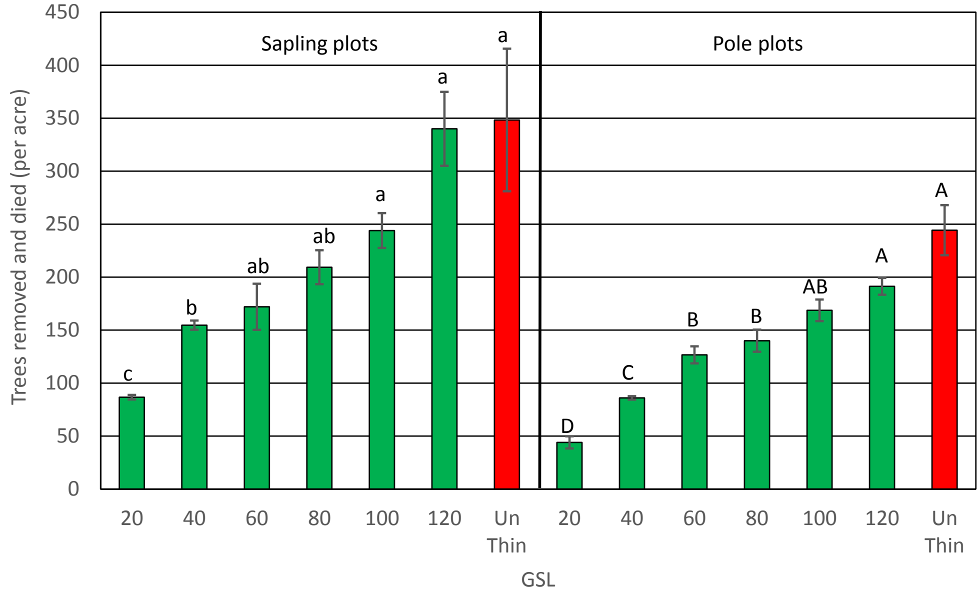


Figure 38—Mean number of trees per acre removed in the GSL (1963 to 2010) and died in the unthinned plots (1978 to 2010). Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A11 for complete description of the analysis.

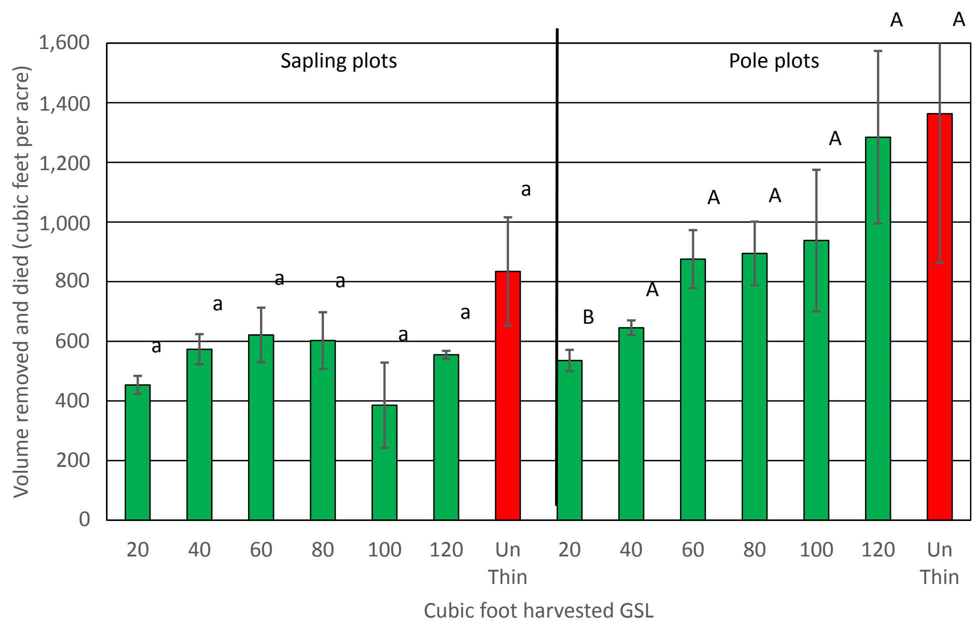


Figure 39—Mean amount of cubic foot volume removed on the sapling and pole GSL plots from 1963 through 2010 and the mean amount lost in the unthinned sapling and pole plots. Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A12 for complete description of the analysis.

The pole plots yielded significantly more total cubic volume than did the sapling plots (Appendix A table A13, sapling/pole effect, probability > F, 0.0002, fig. 40). Within the pole plots the highest yield (2,737 to 4,226 cubic feet per acre) occurred in the GSL 60 through 120 plots. The same similarity in cubic volume yield occurred among GSL 60 through 120 in the sapling plots but the amounts ranged from 2,514 to 3,277 cubic feet per acre (fig. 40). This indicates the thinnings captured tree mortality that would have occurred in them if they would not have been thinned. The yield of the pole GSL 120 plots was larger, though not significantly, than the standing volume on the unthinned pole plots. A similar trend occurred within the sapling plots as no differences were detected in the yields of the 60 through 120 GSLs and the unthinned plots (fig. 40).

The pole plots had considerably and significantly more merchantable cubic feet yield than the sapling plots (Appendix A table A14, sapling/pole effect, probability > F, 0.0059, fig. 41). No differences were detected among the cubic volume yields of pole GSLs 60 through 120 and the amounts ranged from 2,594 to 3,120 cubic feet per acre (fig. 41). The total cubic merchantable yield of the pole GSL 60 plots was greater (not significantly) than GSLs 80, 100, and 120, which all had more BA and TPA. Also, the merchantable cubic volume yield of the unthinned pole plots was similar to the yield of GSLs 20 and 40. Sapling plots had a lower merchantable cubic volume yield than the pole plots and GSLs 40 through 120 all had similar yields that ranged from 1,596 to 2,020 cubic feet per acre (fig. 41). The standing cubic volume in the unthinned sapling plots was similar to the yield of GSLs 40 through 120 (fig. 41).

Analogous to the merchantable cubic yield, the pole plots had significantly larger Scribner board feet volume yield than the sapling plots (Appendix A table A15, sapling/pole effect, probability > F, 0.0022, fig. 42). The pole GSLs 80, 100, and 120 had similar board foot yields ranging from 12,660 to 14,018 board feet per acre. The board foot yield of pole GSL 40 (7,407 board feet per acre) and 60 (9,487 board feet per acre) were comparable and were similar to the standing volume in the unthinned pole plots (fig. 42). Sapling GSLs 40 through 120 all had similar board foot yields ranging from 7,553 in GSL 40 plots to 9,387 board feet per acre in the GSL 80 plots (fig. 42). Being similar to board foot volumes in these GSL plots, the unthinned sapling plots contained 10,053 board feet per acre.

Volume production, and in this case merchantable volume yield, is a compromise between tree density and QMD (figs. 41–43). For total merchantable volume yield in 2010, the 60 and 80 GSL for both the sapling and pole plots show a good balance between QMD and volume production (fig. 43). In particular, the pole GSL 80 plots had a QMD of 12.7 inches and had a 2010 volume yield of 12,660 board feet per acre. The pole GSL 100 (13,507 board feet per acre) and GSL 120 (14,018 board feet per acre) plots had greater yields although they were not significantly larger than the yield of the pole GSL 80 plots (figs. 42, 43).

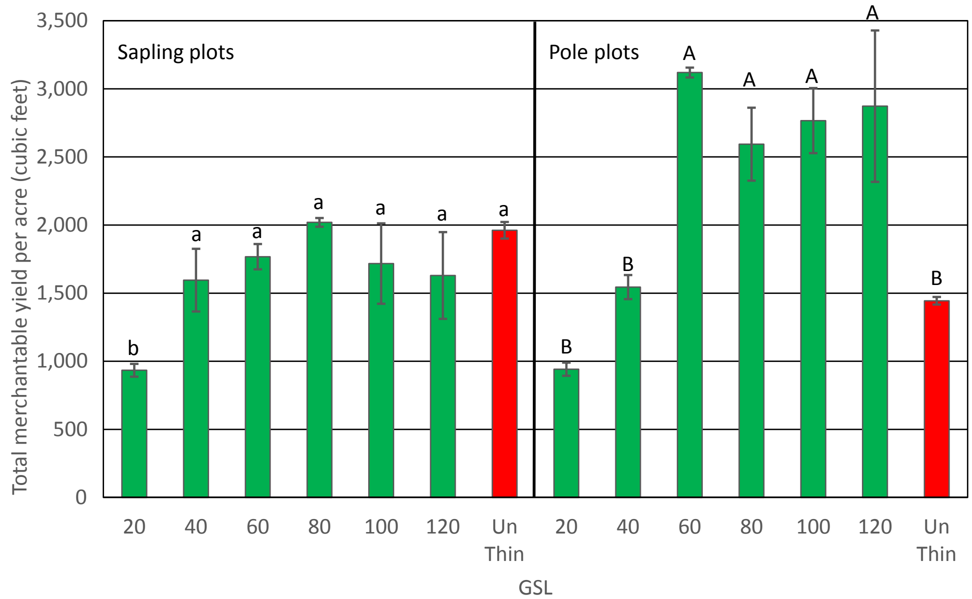


Figure 40—Mean cubic foot volume yield (volume harvested plus standing volume) in the sapling and pole GSL plots through 2010 and the standing mean cubic foot volume in the unthinned plots in 2010. Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A13 for complete description of the analysis.

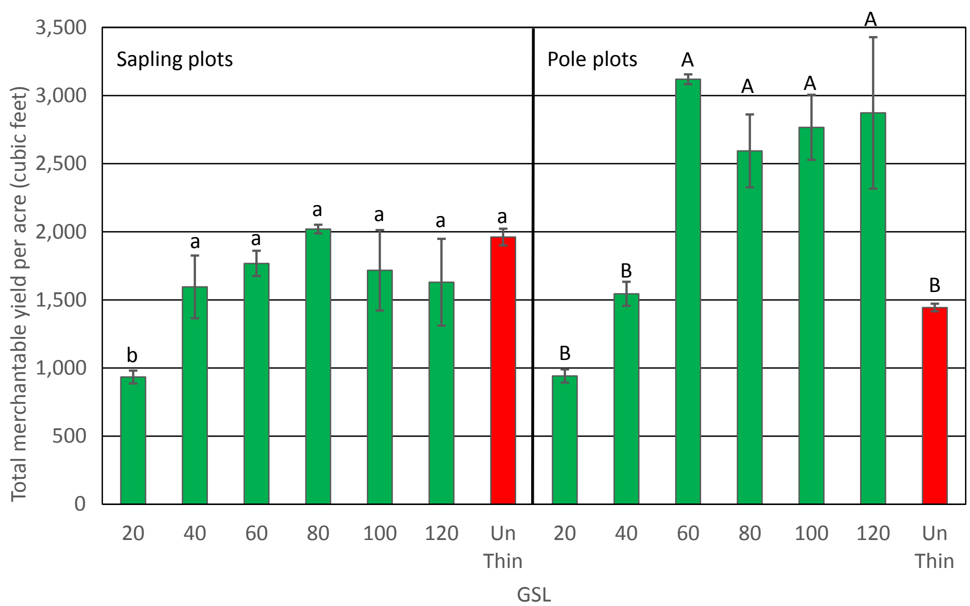


Figure 41—Mean merchantable cubic foot volume yield (volume harvested plus standing volume) in the sapling and pole GSL plots through 2010 and the standing merchantable cubic foot volume in the unthinned plots in 2010. Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A14 for complete description of the analysis.

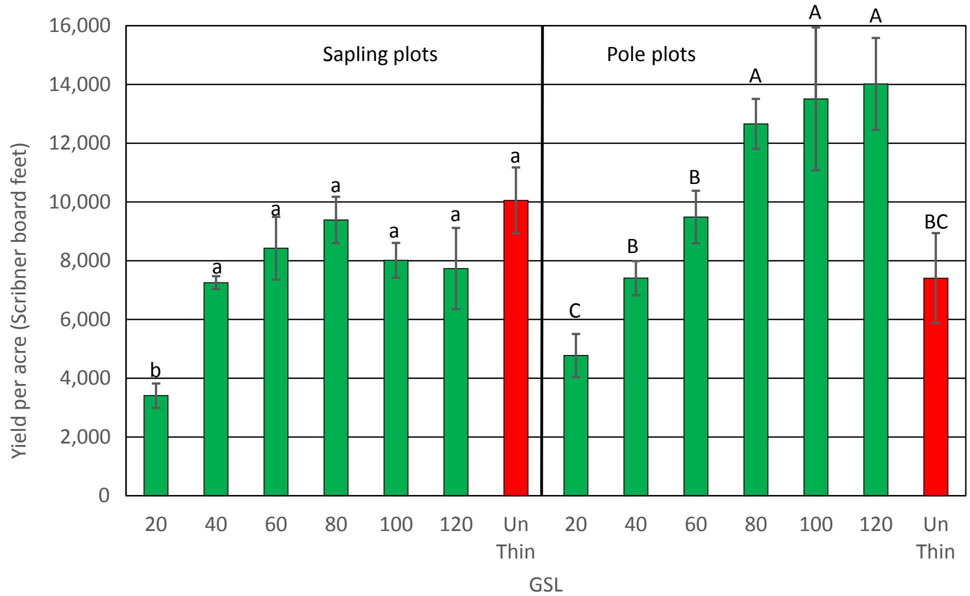


Figure 42—Mean Scribner board feet volume yield per acre (volume harvested plus standing volume) in the sapling and pole GSL plots through 2010 and the standing board foot volume in the unthinned plots in 2010. Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences among GSL and unthinned sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A15 for complete description of the analysis.

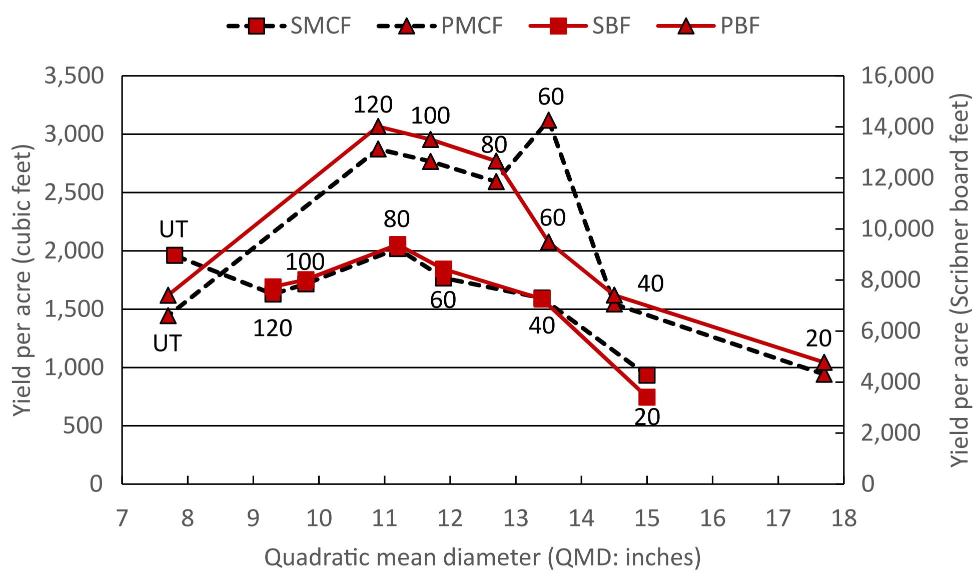


Figure 43—Mean yield per acre in board feet and mean merchantable cubic feet per acre plotted in relation to quadratic mean diameter (QMD) in 2010 for each GSL (20 through 120) and unthinned plots (UT), for both the sapling (SMCF = sapling merchantable cubic feet yield, SBF = sapling board feet yield) and pole plots (PMCF = pole merchantable cubic feet yield, PBF = pole board feet yield).

Mountain Pine Beetles

As mentioned earlier, the tree density management strategies described by the GSL concept are excellent in theory but difficult to apply. The timing and volume removed during the thinnings from 1963 through 2010 were insufficient to maintain the desired BA and TPA as Myers (1967) proposed (figs. 12, 13). As a result, tree densities in both the sapling and pole plots often exceeded their target densities. These different thinning regimes of both sapling- and pole-sized trees did not follow the GSL concept but they did disclose different volumes and yields that can be achieved in the ponderosa pine forests of the Black Hills. These data indicate tree densities created in the GSL 60, 80, and 100 plots offer a good balance between merchantable QMDs and volume production (fig. 43). Such forest management strategies did fulfill the objectives set forth by Myers (1967) and Myers and Boldt (1961), showing how different GSLs influence the development of ponderosa pine forests. However, mountain pine beetles (MPBs) by far are the major determinant of how Black Hills forests develop and influence management strategies (Graham et al. 2016).

MPBs are a documented endemic and epidemic disturbance affecting the ponderosa pine forests in the Black Hills for over a century. A major MPB epidemic killing millions of trees over the entire Hills occurred in the late 1800s through 1908 (Graham et al. 2016). Additional but less severe MPB outbreaks occurred at approximately 20-year intervals and, beginning in earnest in 2009 through 2012, a major epidemic killed millions of trees in the central Hills (fig. 44) (Harris 2013). With the Black Hills Experimental Forest (BHEF) located in the heart of the epidemic, the 2014 Forest Health Protection of the Rocky Mountain Region's (USFS Region 2) MPB survey of the Hills showed the center of the BHEF heavily infested with MPBs (Harris 2014) (fig. 45). Because of its inaccessibility due to topography, this area had no trees removed for many decades. However, the remainder of the BHEF has been actively managed over the last 30 years creating a variety of forest structures and densities except where the GSL plots were located. As a result, MPB caused tree mortality on the BHEF was considerably less than the surrounding landscape (figs. 45, 46). With trees in the GSL plots exposed to abundant MPB populations, all of the GSL plots had trees killed within them during this recent MPB epidemic.

In 2010, the forest treatments implemented to maintain the desired GSL showed promise and provided several options for producing wood products that could be used for a variety of forest management objectives. The BA in 2010 of the sapling GSLs ranged from 29 to 131 square feet per acre and the BA of pole GSLs ranged from 26 to 122 square feet per acre (Appendix A table A16, fig. 47). From 2010 through 2014, MPBs severely impacted all of the GSLs and trees across all QMDs with the exception of both the sapling and pole 20 GSLs and there was no significant difference in how MPBs impacted the sapling and pole plots (Appendix A table A16, sapling/pole effect probability > F 0.7653). The sapling GSL 20 plots lost 25 percent (7.3 square feet) of their BA and the pole GSL 20 plots lost 22 percent (5.7 square feet of their BA to MPBs, but these losses were not statistically significant (fig. 47).

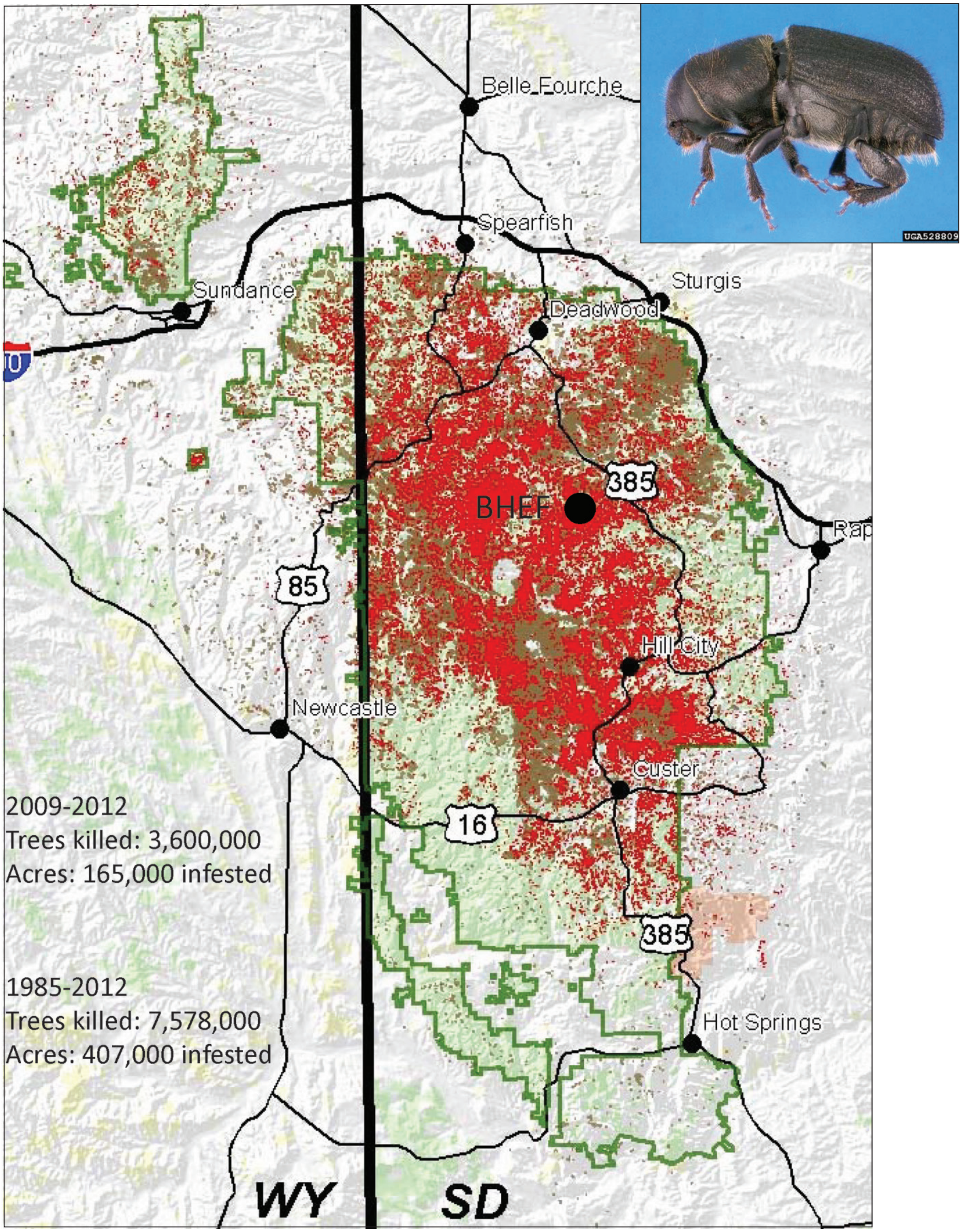


Figure 44—By 2012, the Black Hills Experimental Forest (BHEF) was intensely exposed to MPBs (shaded red) (Harris 2013) (mountain pine beetle photo by Erich G. Vallery, USDA Forest Service, SRS-4552, Bugwood.org).

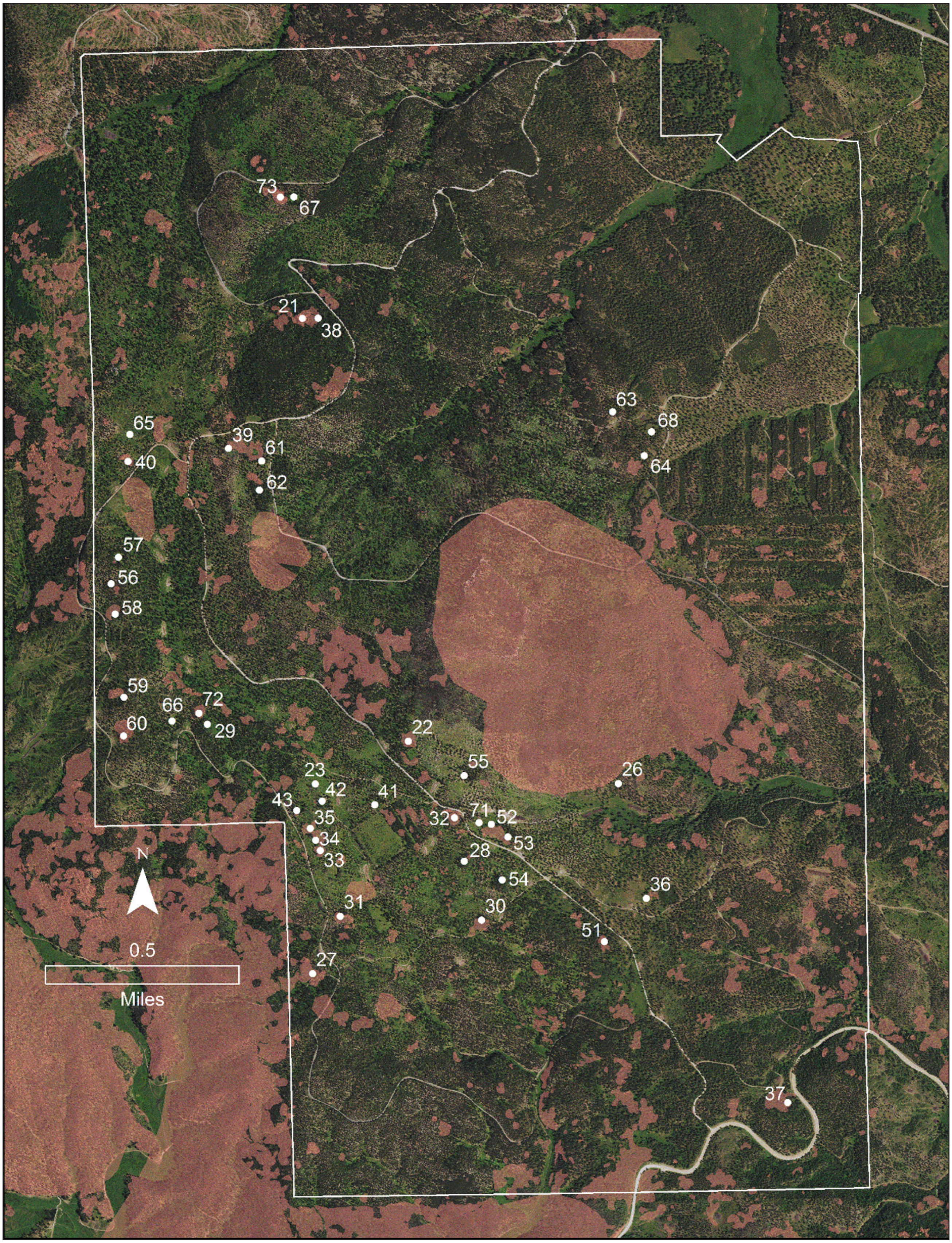


Figure 45—Mountain pine beetles (MPBs) killed (red areas) trees throughout the Black Hills Experimental Forest (BHEF) from 2000 through 2012 with the center of the Forest heavily impacted by MPBs (Harris 2013). The BHEF boundary and MPB caused tree mortality is displayed over a 2014 National Agriculture Imagery Program (NAIP) image (1 m resolution).

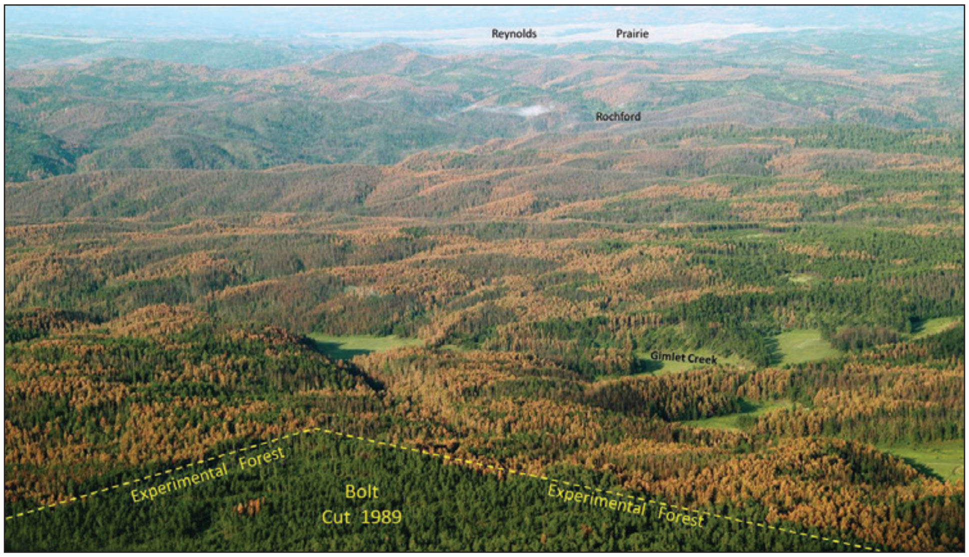


Figure 46—MPBs were very active around the Black Hills Experimental Forest beginning in 2010, and in 2013 the effect of reducing stand density on the Experimental Forest beginning in 1989 through 2013 was very effective in reducing MPB attacks. Photograph taken in August 2013 looking southwest by Ben Wudtke, Black Hills Forest Resource Association.

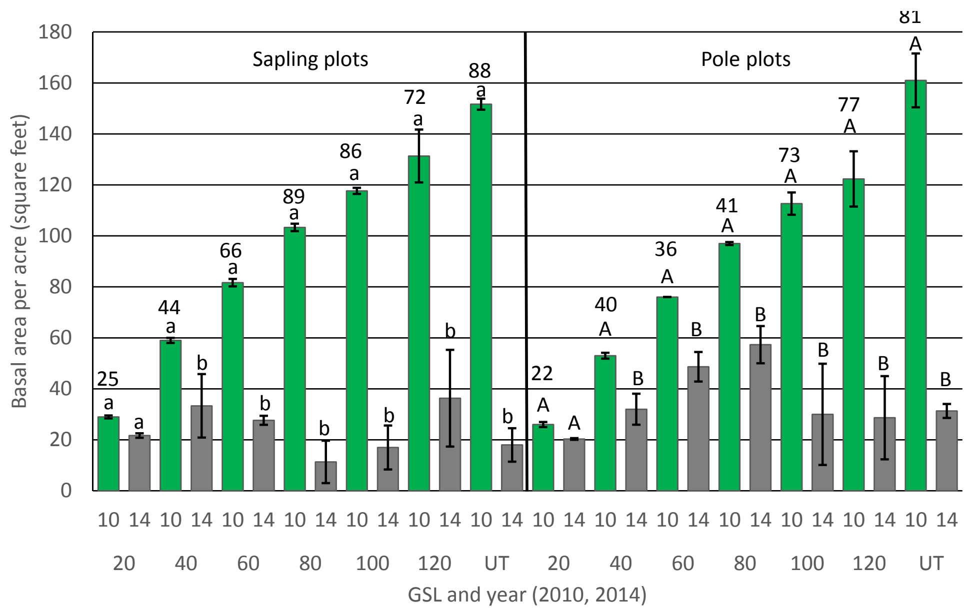


Figure 47—The 2010 basal area per acre for the GSL and unthinned (UT) sapling and pole plots, and the basal area per acre for the same plots in 2014. The decrease in basal area per acre within the plots between 2010 and 2014 was the result of trees being killed by mountain pine beetles (MPBs). Numbers above the bars indicate the percentage change in basal area per acre between 2010 and 2014 caused by MPBs. Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences between 2010 and 2014 values for the GSL and unthinned sapling plots (different letters a, b) and within the pole plots (different letters A, B) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A16 for complete description of the analysis.

The BA losses caused by MPBs from 2010 through 2014 within the other GSLs for both the poles and saplings were significant. In 2010, the sapling GSL 80 plots had 103 square feet of BA and in 2014 they had 11 square feet of BA, a loss of 89 percent to MPBs (fig. 47). The most BA lost to MPBs on the pole GSL plots was

77 percent (94 square feet per acre) that occurred on the GSL 120 plots. Eighty-eight percent of the BA was lost to MPBs on the unthinned sapling plots that had 152 square feet of BA in 2010 and 18 square feet in 2014. The unthinned pole plots had 161 square feet of BA in 2010 and 31 square feet in 2014, which equaled an 81 percent loss (fig. 47). Graham et al. (2016) suggested stands containing 40 to 80 square feet of BA were resistant to MPB attack but all of the GSL including those with BA less than 80 square feet had trees killed. Of particular note was the sapling GSL 20 plots with 26 square feet per acre of BA and the pole GSL 20 plots with 29 square feet of BA both had trees killed by MPBs (fig. 47).

The GSL concept used both BA and TPA depending on d.b.h. to establish the different thinning regimes (Myers 1967). As a result, the sapling plots had more TPA than the pole plots and lost significantly more trees to MPBs than the pole plots (Appendix A table A17, sapling/pole effect probability > F < 0.0001, fig. 48). In 2010, the sapling GSL 120 plots contained 277 TPA and by 2014, 191 TPA had been killed (69 percent) by MPBs resulting in 87 TPA living in 2014 (fig. 48). The sapling GSL plots 20 and 40 lost a statistically insignificant amount of trees to MPBs between 2010 through 2014, as did the pole GSLs 20, 40, and 60 plots (fig. 48). The greatest TPA killed by MPBs occurred on the unthinned plots, with the sapling plots losing 341 TPA (74 percent) which resulted in 121 TPA living in 2014. The unthinned pole plots lost 363 TPA (72 percent) resulting in 142 TPA living in 2014 (fig. 48). Within the GSL plots, the sapling 120 plots lost the most TPA with 190 (69 percent) killed by MPBs and the pole GSL 120 plots lost 149 TPA or 78 percent with both values showing the greatest loss to MPBs among the pole GSLs (fig. 48). With these tree losses to MPBs, all forms of volume were significantly impacted by MPBs.

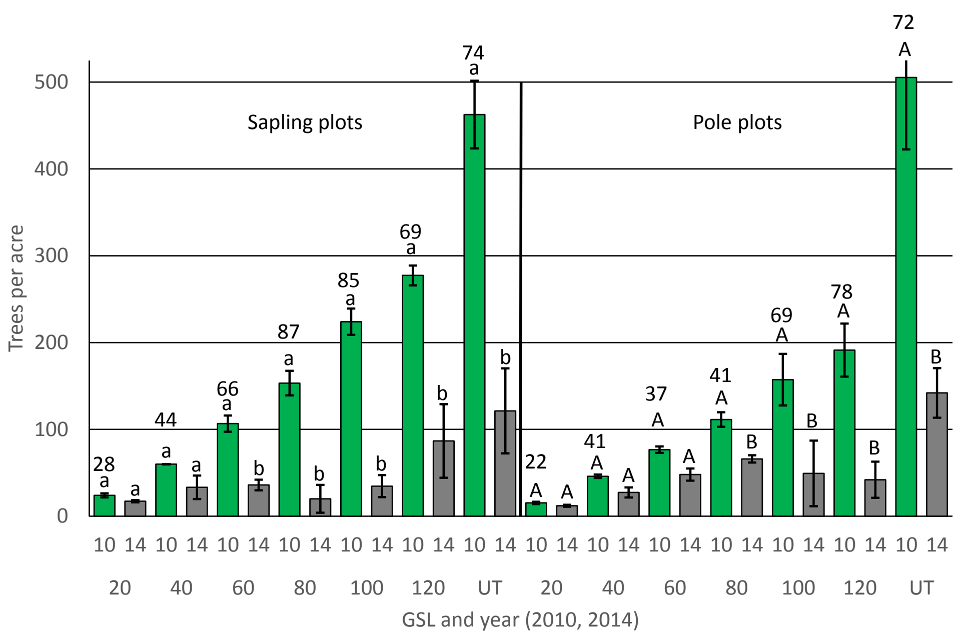


Figure 48—The 2010 trees per acre for the GSL and unthinned (UT) sapling and pole plots, and the trees per acre for the same plots in 2014. The decrease in trees per acre within the plots between 2010 and 2014 was the result of trees being killed by mountain pine beetles (MPBs). Numbers above the bars indicate the percentage change in trees per acre between 2010 and 2014 caused by MPBs. Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences between 2010 and 2014 values for the GSL and unthinned sapling plots (different letters a, b) and within the pole plots (different letters A, B) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A17 for complete description of the analysis.

Using 2010 cubic feet volume as an indicator, MPBs equally impacted the sapling and pole plots (Appendix A table A18, sapling/pole effect probability > F 0.1006, fig. 49). In 2010, the maximum cubic feet per acre on the sapling GSLs occurred on the 120 plots with 2,722 cubic feet per acre. Similarly, the pole GSL 120 plots had 2,942 cubic feet per acre in 2010, which was the maximum that occurred on the pole GSL plots (fig. 49). The sapling GSL 120 plots significantly lost 74 percent (2,018 cubic feet per acre) of their cubic volume per acre to MPBs and the pole 120 plots lost 75 percent (2,213 cubic feet per acre) of their cubic volume to MPBs from 2010 through 2014. No difference was detected between the 2010 and 2014 cubic volumes for the sapling GSL 20 and pole GSL 20 plots (fig. 49). MPBs killed 3,067 cubic feet per acre in the unthinned pole plots and 3,100 cubic feet per acre in the sapling plots with both values being the greatest losses the MPBs inflicted on the plots in terms of cubic volume (fig. 49).

MPBs equally impacted the sapling and pole plots using merchantable cubic feet as an indicator (Appendix A table A19, sapling/pole effect probability > F 0.4345, fig. 50). Both the sapling and pole GSL 20 plots had no significant losses of merchantable cubic foot volumes to MPBs from 2010 through 2014, but all of the other plots did (fig. 50). The GSLs 80, 100, and 120 sapling plots or those with the higher tree densities had both the greatest amount and percentage loss of merchantable cubic volume to MPBs than any other GSL plot including the pole plots (fig. 50). The sapling GSL 80 plots lost 1,787 merchantable cubic feet per acre (91 percent), GSL 100 plots lost 1,446 cubic feet (87 percent), and the sapling GSL 120 plots lost 1,247 cubic feet per acre (81 percent) of merchantable volume to MPBs.

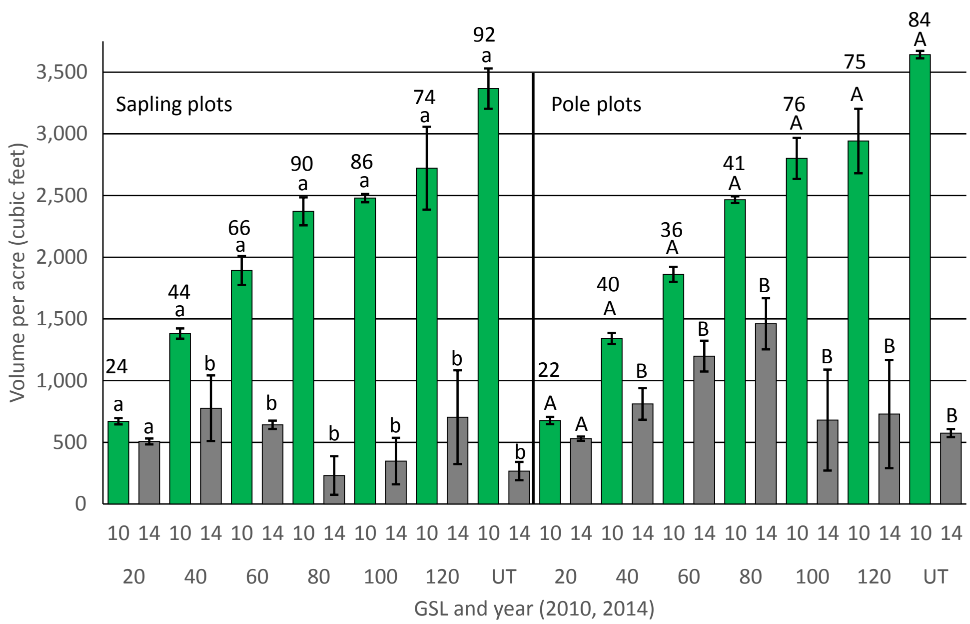


Figure 49—The 2010 mean cubic feet per acre for the GSL and unthinned (UT) sapling and pole plots, and the mean cubic feet for the same plots in 2014. The decrease in cubic foot volume per acre within the plots between 2010 and 2014 was the result of trees being killed by mountain pine beetles (MPBs). Numbers above the bars indicate the percentage change in cubic feet per acre between 2010 and 2014 caused by MPBs. Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences between 2010 and 2014 values for the GSL and unthinned sapling plots (different letters a, b) and within the pole plots (different letters A, B) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A18 for complete description of the analysis.

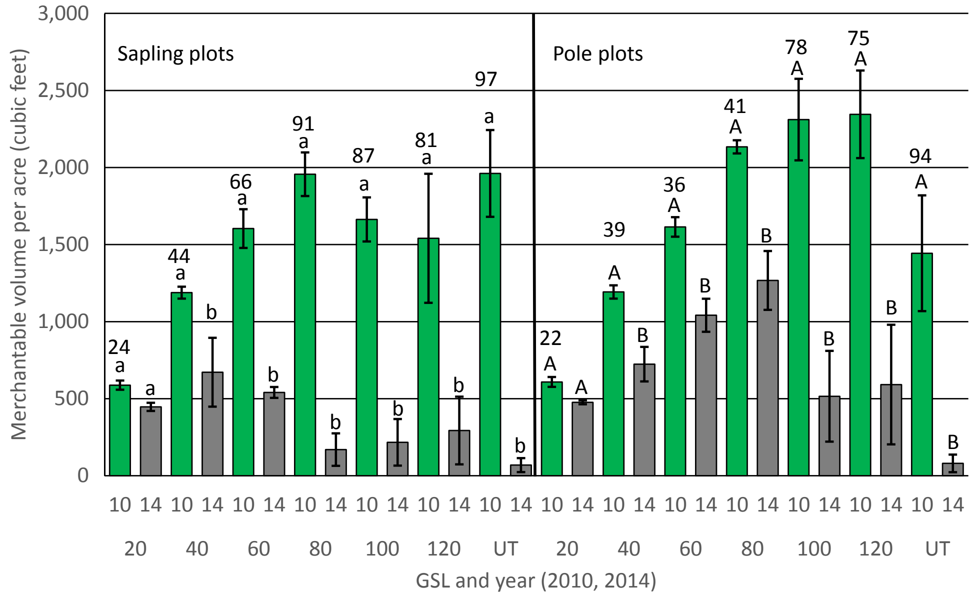


Figure 50—The 2010 mean merchantable cubic feet per acre for the GSL and unthinned (UT) sapling and pole plots, and mean merchantable cubic feet per acre for the same plots in 2014. The decrease in the merchantable cubic feet per acre volume within the plots between 2010 and 2014 was the result of trees being killed by mountain pine beetles (MPBs). Numbers above the bars indicate the percentage change in merchantable cubic feet per acre between 2010 and 2014 caused by MPBs. Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences between 2010 and 2014 values for the GSL and unthinned sapling plots (different letters a, b) and within the pole plots (different letters A, B) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A19 for complete description of the analysis.

Although not significant, MPBs tended to have a lesser impact in terms of merchantable cubic volume (132 to 867 cubic feet per acre) loss to MPBs within the pole plots compared to the sapling plots (fig. 50). The pole GSL 20 plots lost 22 percent of their 2010 merchantable volume to MPBs by 2014, the GSL 40 plots lost 39 percent, GSL 60 plots lost 36 percent, and the GSL 80 pole plots lost 41 percent of their 2010 merchantable cubic volume to MPBs by 2014. These losses were less than those experienced by the pole GSL 100 and GSL 120 plots. The pole GSL 100 plots lost 1,795 merchantable cubic feet per acre (78 percent) and the pole GSL 120 plots lost 1,754 cubic feet per acre (75 percent) from 2010 through 2014 to MPBs (fig. 50). The unthinned sapling plots lost the most merchantable cubic volume (1,892 cubic feet per acre, 97 percent) to MPBs and the unthinned pole plots lost 1,363 cubic feet per acre (94 percent) to MPBs by 2014 compared to 2010 (fig. 50). The impact MPBs had in terms of board feet were nearly identical to those expressed by merchantable cubic feet (Appendix A table A20, sapling/pole effect probability > F 0.4345, fig. 51). Again, the sapling GSL 80 plots were impacted by MPBs the most and, in general, the pole plots fared better in the face of MPBs than did the sapling plots in terms of board foot losses.

Even though MPBs have been studied for over a century, a complete understanding of the mechanisms and conditions in which they attack and kill trees is far from known (Graham et al. 2016). Data from these GSL plots show MPBs will attack and kill ponderosa pine trees in stands with very low densities. Although Graham et al. (2016) suggested that changes in tree density of plots with a common border influences MPB

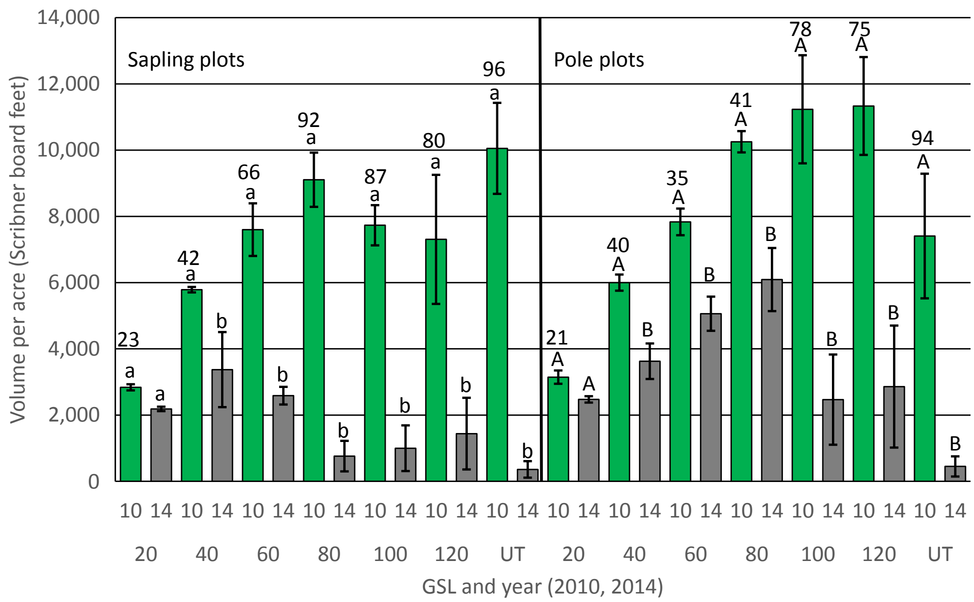


Figure 51—The 2010 mean Scribner board feet per acre for the GSL and unthinned (UT) sapling and pole plots, and the mean board feet per acre for the same plots in 2014. The decrease in board foot volume per acre within the plots between 2010 and 2014 was the result of trees being killed by mountain pine beetles (MPBs). Numbers above the bars indicate the percentage change in board feet per acre between 2010 and 2014 caused by MPBs. Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences between 2010 and 2014 values for the GSL and unthinned sapling plots (different letters a, b) and within the pole plots (different letters A, B) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A20 for complete description of the analysis.

activity, findings concerning MPBs in these GSL plots confound such a conclusion. Nevertheless, how MPBs impacted these GSL plots reinforces the suggestion that forest density strategies need to occur over large (thousands of acres) landscapes to offer the greatest forest resistance to MPB attack. Also demonstrated, especially within the pole GSL plots densities ranging from 40 to 80 square feet per acre of BA, still appear to be a reasonable target for offering some resilience and resistance of ponderosa pine forests from epidemic MPBs (Graham et al. 2016).

Other Findings

The productivity of Black Hills ponderosa pine forests as Meyer (1938) and Myers and Van Deusen (1960b) indicated is low with site indexes ranging from 40 to 70 with a mean of 57 (100-year base). Meyer (1938) grouped the site indexes into seven site quality classes with class I having a mean site index of 120, class IV a mean of 78, class VI a mean of 50, and site class VII, the lowest described, with a mean site index of 36. The site index of the Black Hills Experimental Forest was estimated at 55. Using the heights of the trees on the GSL plots at age 100, the pole plots had a mean site index of 60 and the sapling plots a mean site index of 52 confirming the 55 site index estimate (fig. 32). Until the advent of growth models, such as FVS, the amount of wood (yield) produced in a forest stand was estimated by determining the site index (i.e., height for a given tree age and corresponding site index curve) and the yield of even-aged stands was estimated for the corresponding age and tree density (BA and TPA) proportional to the “normal” stand described in the yield tables (Haig 1932; Meyer 1938). In addition to displaying standing volumes, diameters, and tree densities for different-aged stands, these stand yield tables also described the volume increment that could be expected for each site index at different ages and periods.

Mean Annual Increment (MAI)

Within each site class, mean annual increment (MAI) was a common metric used to describe the productivity of a stand over its life (Haig 1932; Meyer 1938). MAI is simply the volume (e.g., cubic, board feet) at given stand age divided by that age. Although the GSLs and unthinned plots do not represent all possible even-aged forest conditions that occur in the Black Hills at a given age, they are very representative. In addition, tree densities among the plots were highly variable resulting in a wide range of MAIs. The mean annual cubic foot per acre increments varied considerably but they tended to peak or culminate at 95 to 105 years of age (fig. 52). This point of culmination, or period at which maximum mean annual growth occurs, is usually considered the stand's rotation age. A stand cut at this time will yield the maximum volume return per year of growth (Haig 1932).

Periodic Annual Increment (PAI)

A second metric frequently used to describe forest productivity is periodic annual increment (PAI) and often BA (PAI-BA, square feet per acre per year) and cubic volume increment (PAI-CF, cubic feet per acre per year) are used. These metrics describe periodic mean annual increment for approximately 5- or 10-year intervals through the life of a stand (Haig 1932; McArdle and Meyer 1930; Meyer 1938). In general, the periodic increment for forest trees and stands is greater in their younger years and their periodic increment decrease as stands age (Barnes et al. 1998; Haig 1932; Meyer 1938). In addition, stand structure (e.g., density) influences periodic increment differences, although not great, were detected among the PAI-CF

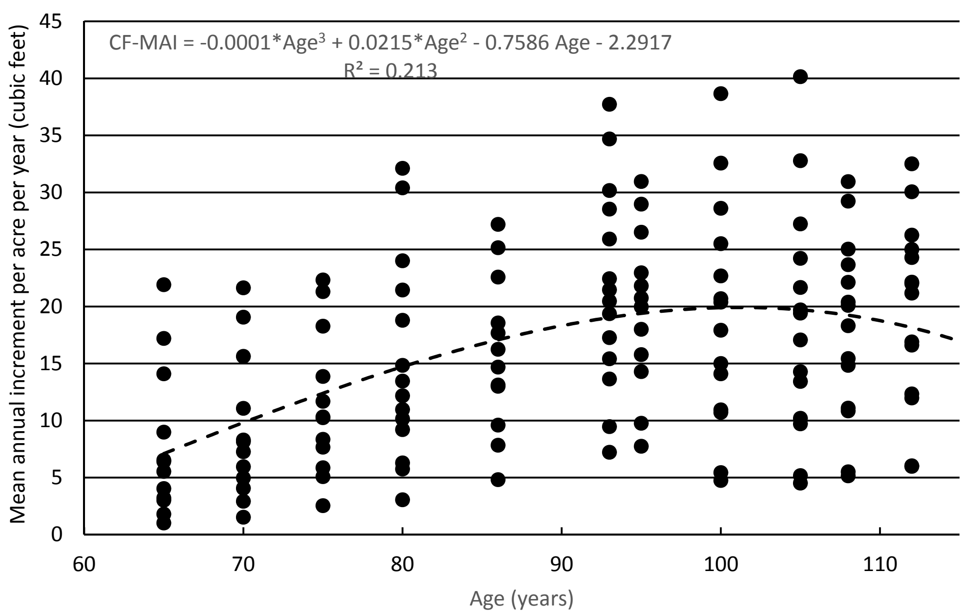


Figure 52—Mean annual cubic foot (cubic feet per acre per year) increment (MAI) for the GSL and unthinned plots from age 65 years through 112 years.

and PAI-BA among the GSLs (Appendix A tables A21, A22 GSL effect probability > F < .0001, sap/pole effect probability > F < 0.1101 saplings, 0.4268 poles; figs. 53, 54). Rather than defined intervals, the period between measurements (2 to 7 years) from 1963 through 2010 for the GSLs and 1978 through 2010 for the unthinned plots were used to compute periodic annual increment rates. The 1998 through 2003 period when the major thinning occurred in each plot was omitted and the calculations did not include the 2010 through 2014 period when MPBs killed many trees. There was considerable variation in BAI among the sapling and pole plots with no significant difference discovered in mean PAI-BA between the sapling and pole plots (fig. 53). The sapling GSL 80 plots had a mean PAI-BA of 2.4 square feet per acre per year and the pole GSL plots had a mean PAI-BA of 1.8 square feet per acre per year over the course of the study. These PAI-BA means were similar to those occurring on the GSL 100 and 120 (fig. 53). The smallest PAI-BA mean occurred on GSLs 20, 40, and the unthinned plots. However, these means were not significantly different from those occurring on the GSL 100 (saplings 2.3 square feet per acre per year and poles 1.4 square feet per acre per year) and the GSL 120 saplings (1.1 square feet per acre per year and poles 1.5 square feet per acre per year). The lowest PAI-BA means occurred on the unthinned plots with a mean PAI-BA of 0.04 square feet per acre per year on the sapling plots and 0.048 square feet per acre per year on the unthinned pole plots (fig. 53).

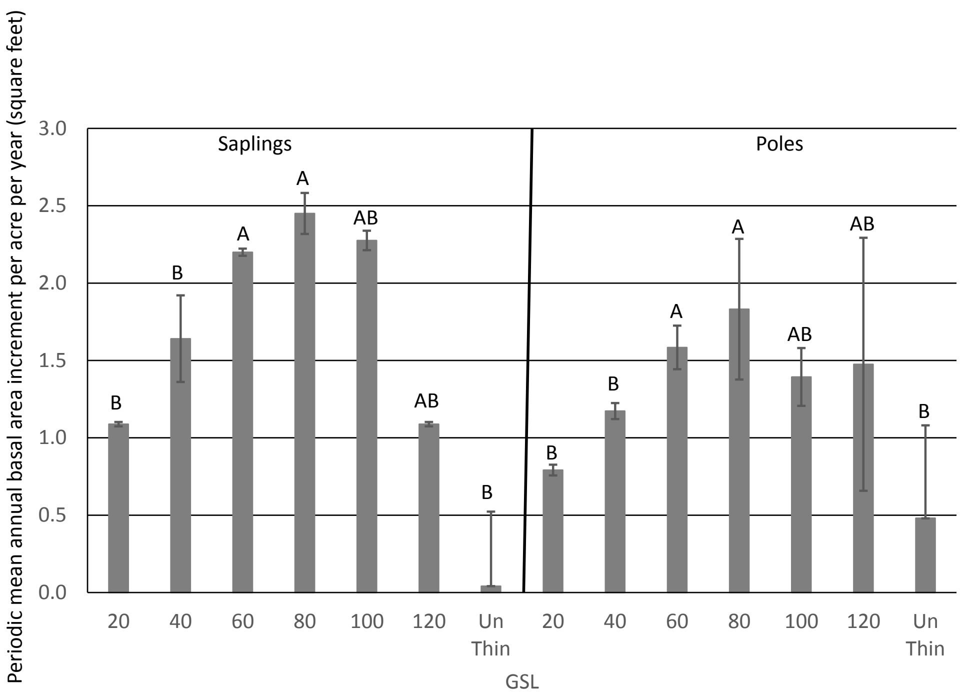


Figure 53—The periodic mean annual basal area (square feet per acre per year) increment (PAI-BA) for the GSL and unthinned (UnThin) sapling and pole plots. The period between measurements (2 to 7 years) from 1963 through 2010 for the GSL and 1978 through 2010 for the unthinned plots were used to compute periodic annual increment. The 1998 through 2003 period when the major thinning occurred in each plot was omitted and the calculations did not include the 2010 through 2014 period when MPBs killed many trees. Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences in mean PAI-BA among the GSL and unthinned plots within the sapling (A, B) and within the pole plots (A, B) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A21 for complete description of the analysis.

The differentiation of periodic annual increment for cubic foot (PAI-CF) among the GSL and the unthinned plots was similar to the differences found with PAI-BA (Appendix A table A22, sapling/pole effect probability > F 0.4268, fig. 54). The most notable change between PAI-BA and PAI-CF was the magnitude of PAI-CF for both plot types. The PAI-CF for the sapling 80 GSL was 61 cubic feet per acre per year and it was 56 for the pole GSL 80 (fig. 54). These means were not significantly different than the PAI-CFs for GSL 100 (sapling, 54 cubic feet per acre per year; pole 51 cubic feet per acre per year) and GSL 120 (sapling, 60 cubic feet per acre per year; pole 49 cubic feet per acre per year) (fig. 54). Even though not significantly different, the unthinned sapling plots had a PAI-CF of 12 cubic feet per acre per year and the unthinned pole plots had a PAI-CF of 53 cubic feet per acre per year. This outcome was related to the large amount of variation in the means as indicated by the error bars (fig. 54).

Periodic mean annual increment for cubic volume (PAI-CF) for each of the GSL and for seven periods from 1963 through 2006 were computed before MPB caused tree mortality occurred. The periods varied in length from 2 to 11 years and the 1973 to 1978 and 1998 to 2003 periods were not used because major thinnings took place. The PAI-CFs for the sapling plots were significantly different from those occurring on the pole plots. Therefore, the PAI-CF means were grouped within each plot type (Appendix A table A23, fig. 55). This difference is exemplified by the sapling GSL 20 plots at age 70 had a PAI-CF of 9.5 cubic feet per acre per year, and the pole GSL 20 plots had a PAI-CF of 18.2 cubic feet per acre per year. During this period, the sapling plots contained 11.3 square feet of BA and the pole plots contained 20.0 square feet of BA (figs. 55, 56).

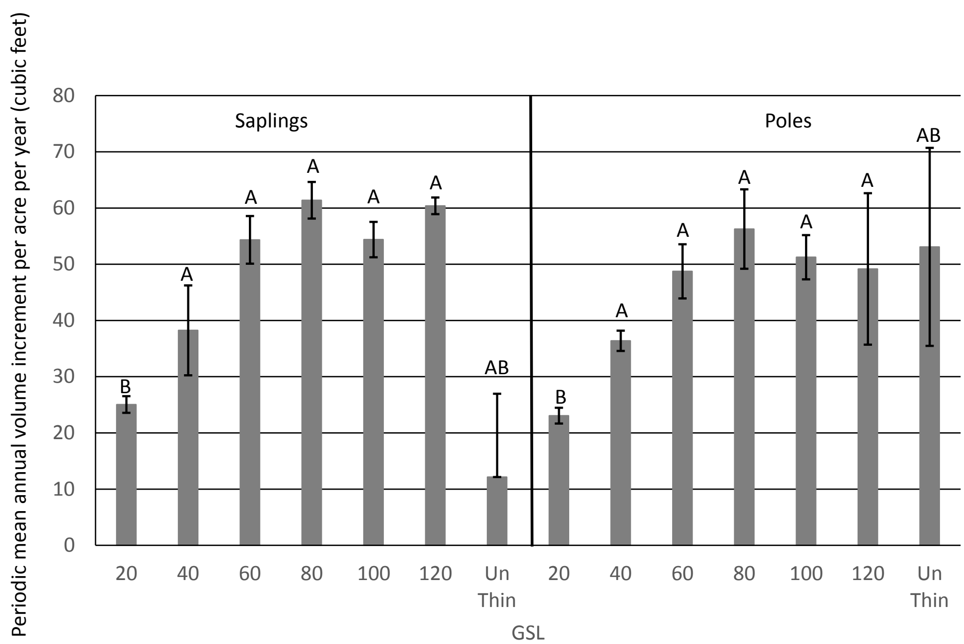


Figure 54—The periodic mean annual cubic volume (cubic feet per acre per year) increment (PAI-CF) for the GSL and unthinned (UnThin) sapling and pole plots. The period between measurements (2 to 7 years) from 1963 through 2010 for the GSL and 1978 through 2010 for the unthinned plots was used to compute periodic annual increment. The 1998 through 2003 period when the major thinning occurred in each plot was omitted and the calculations did not include the 2010 through 2014 period when MPBs killed many trees. Vertical bars are the standard errors of the means. Significant (alpha = 0.05) differences in PAI-CF among the GSL and unthinned plots within the sapling (A, B) and within the pole plots (A, B) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A22 for complete description of the analysis.

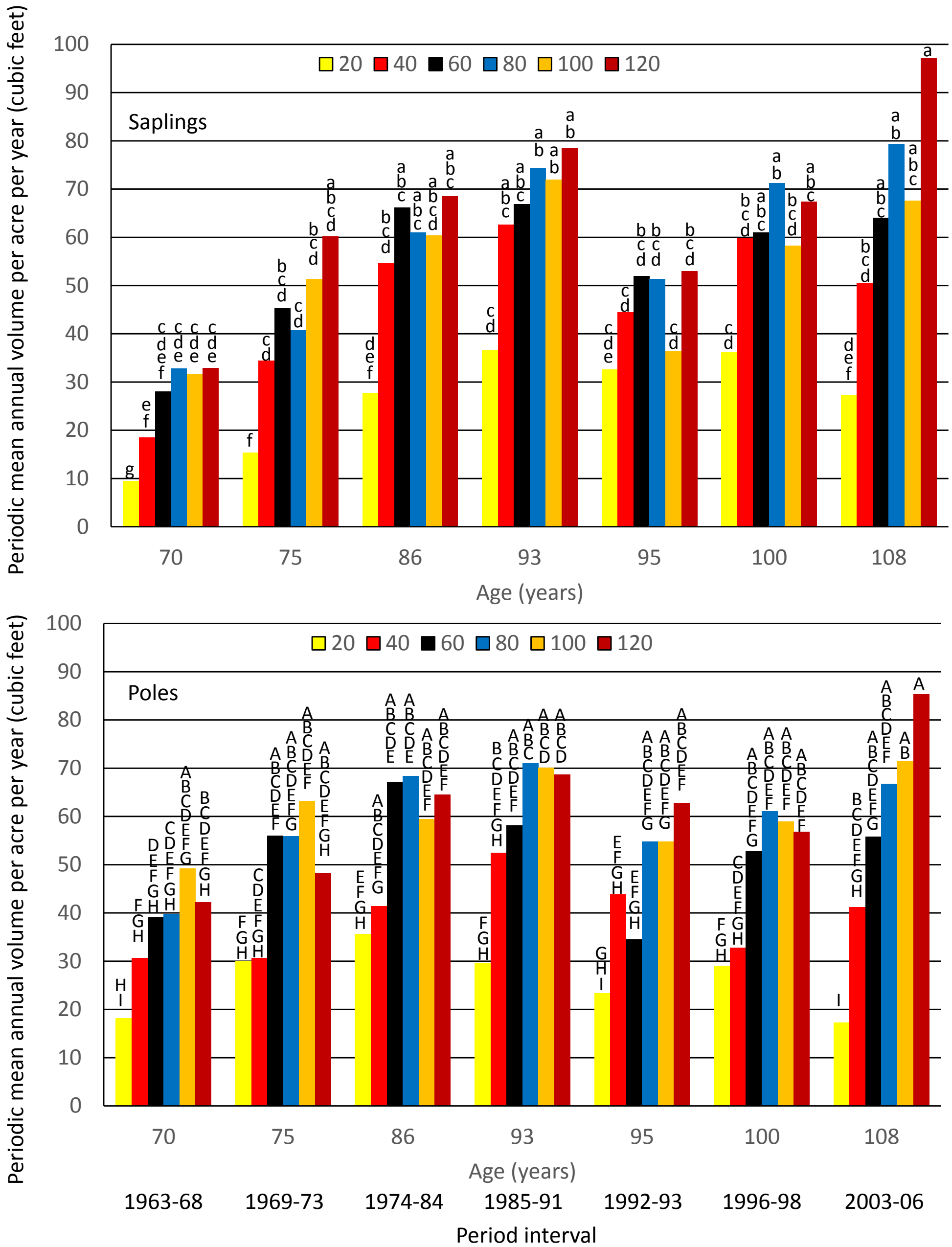
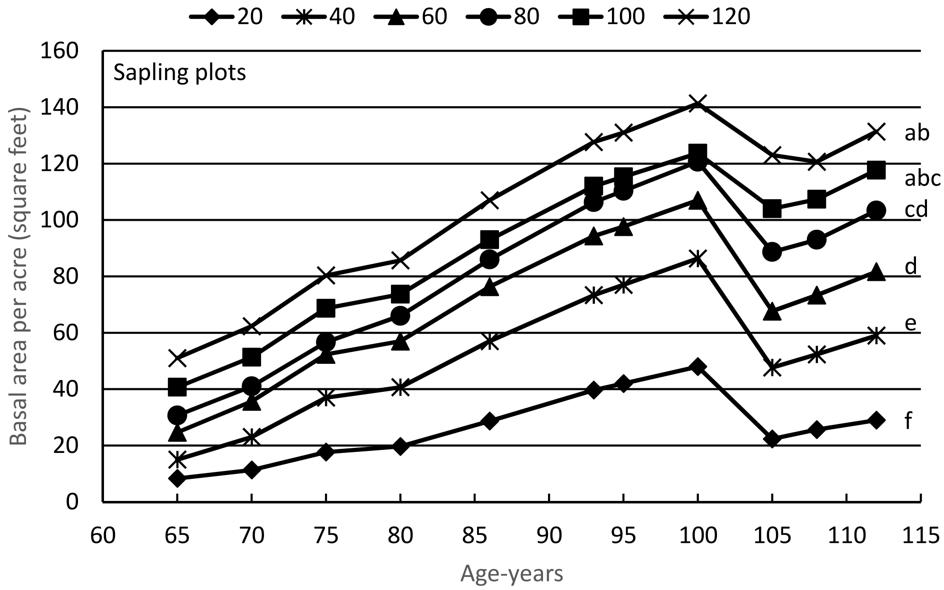


Figure 55—Periodic mean annual cubic volume (cubic feet per acre per year) increment (PAI-CF) for the GSLs and seven different periods from 1963 through 2006. The periods varied in length and the 1973–1978 and 1998-2003 periods were not used as major thinnings took place. Also the 2007–2010 periods were omitted for the sapling GSL 120 and pole GSL 100 and 120 plots as MPBs were impacting those plots. Significant (alpha = 0.05) differences in PAI-CF among the GSL and unthinned plots within the sapling (a, b, c) and within the pole plots (A, B, C) were determined within each plot type using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A23 for complete description of the analysis.



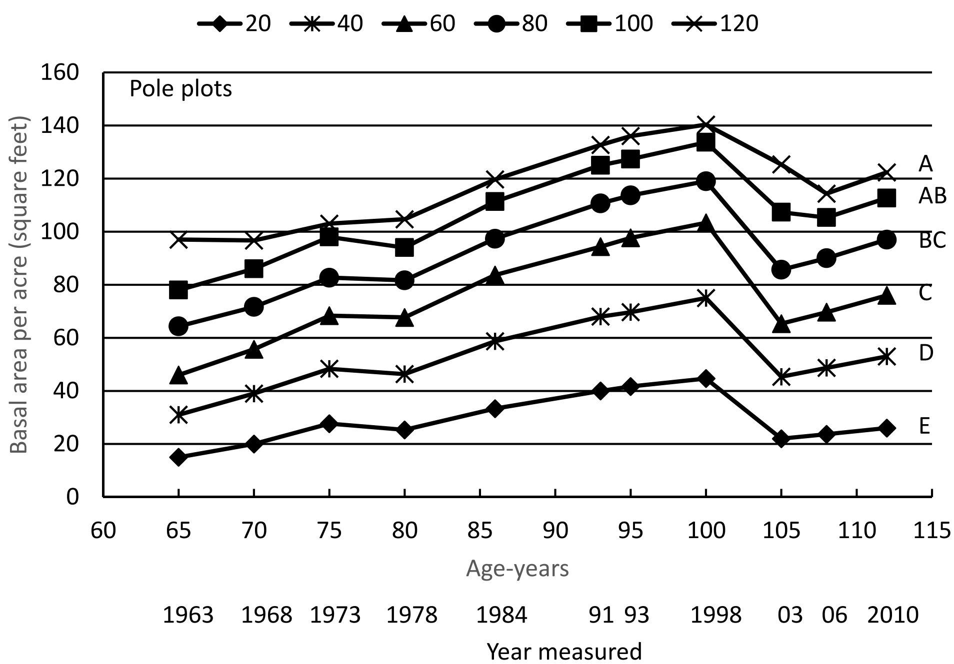


Figure 56—Mean basal area per acre for each of the sapling and pole GSL from 1963 through 2010. Significant (alpha = 0.05) differences among GSL sapling plots (different letters a, b, c) and within the pole plots (different letters A, B, C) were determined using a Generalized Linear Mixed Model (GLMM) and Tukey-Kramer grouping of least squares means. See Appendix A table A23 for complete description of the analysis.

Within each plot type there was considerable PAI-CF variation within and among the GSLs resulting in few unique outcomes. Only in the PAI-CFs of the sapling GSL 20 plots at age 70 and 75 years, pole GSL 20 plots at age 108, and both the sapling and pole GSL 120 plots at age 108 were the PAI-CF means significantly different than the other PAI-CF means within the respective plot group (fig. 55). With the exception of the 2003 through 2006 period, the 1985 through 1991 period had the largest PAI-CFs for both plot types. For example, the PAI-CFs for the GSLs 80, 100, and 120 plots for both the saplings and poles had PAI-CFs near or exceeding 70 cubic feet per acre per year. The sapling GSL 80 plots at the end of this period had 110 square feet of BA and the pole plots 114 square feet of BA; the sapling GSL 100 plots had 115 square feet of BA, the pole GSL 100 plots had 127 square feet of BA, the sapling GSL 120 plots had 131 square feet of BA, and the pole GSL 120 plots had 136 square feet of BA (fig. 56). The largest PAI-CFs occurred on both sapling and pole GSL 120 plots for the period from 2003 through 2006. The sapling GSL 120 plots for this period had a PAI-CF of 97 cubic feet per acre per year and the pole GSL 120 plots had a PAI-CF of 85 cubic feet per acre per year (fig. 55). Both of these means were significantly larger than the other means within the respective plot group. Interestingly, these maximum PAI-CFs occurred after the plots received a major thinning in 1998 and the sapling GSL 120 plots contained 131 square feet of BA and the pole plots contained 122 square feet of BA (fig. 56).

The GSL 20 plots represent the productivity that can be expected at tree densities ranging from 20 to 40 square feet of BA (figs. 55, 56). For example, from 1968 through 1998 and from 2003 through 2006, the BA for the pole GSL 20 plots ranged from 20 to 45 square feet. For these same time periods, the PAI-CFs ranged from 17 to 36 cubic feet per acre per year, with the maximum occurring for the 1974 through 1984 period. With lower BAs (11 to 26 square feet), the sapling GSL 20 plots through 1984 had lower PAI-CFs, but after 1984, the PAI-CFs for the sapling GSL 20 plots equaled and often exceeded the PAI-CFs of the pole GSL 20 plots. However, these PAI-CFs never exceeded 37 cubic feet per acre per year (figs. 54, 55). From 1985 through 1991, the BA of the sapling GSL 40 plots ranged from 29 to 73 square feet per acre (fig. 56). During this period the PAI-CF was 63 cubic feet per acre per year, while in the same time period the pole GSL 40 plots had a PAI-CF of 53 cubic feet per acre per year and the BA ranged from 59 to 68 square feet (figs. 55, 56).

Periodic Annual Increment and Stand Density

Langsaeter (1941) hypothesized that the total production of cubic volume by a stand of given age and composition on a given site is, for all practical purposes, constant and optimum for a wide range of stocking density. It can be decreased but not increased by altering the amount of growing stock to levels outside this range. Using PAI-BA over a wide range of tree densities found in the different GSLs and unthinned plots shows a similar relationship to the one Langsaeter postulated (fig. 57). Some plots with 52 square feet and 107 square feet of BA had PAI-BAs nearly or over 3.5 square feet per year while other plots with similar BAs had in the range of 1.0 square foot per year (fig. 56). Also noteworthy were plots with 20 square feet of BA and 189 square feet of BA, both had PAI-BAs of approximately 1.0 square foot per year (fig. 57). These data show that if target tree densities are desired (i.e., 40 to 80 square feet of BA) for stands resistant to MPBs, a stand may quickly move from resistant to nonresistant when it has a PAI-BA of 3.5 square feet per year (fig. 57). The shape of the curve in figure 57 and the large amount of variation of PAI-BA do not strictly adhere to Langsaeter's postulate. Nevertheless, these data show that site productivity can be similar over a wide range of stand densities within the Black Hills.

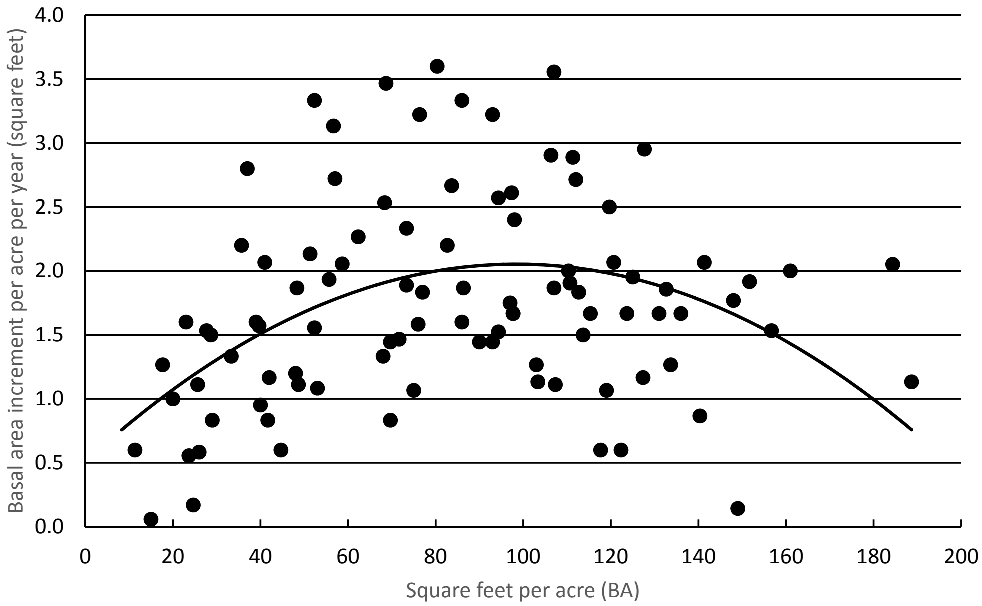


Figure 57—Periodic annual basal area increment (PAI-BA) varied considerably over a wide range of stand densities.

Discussion

The ponderosa pine forests of the Black Hills have low productivity (40 to 70 site indexes) but have supported a thriving lumber industry for over 100 years (Boldt and Van Deusen 1974; Clow 1998; Freeman 2015; Myers and Van Deusen 1960). Because of good cone crops and spring and summer rains, the *scopulorum* variety of ponderosa pine readily regenerates and populates the forest floor in response to openings created in the forest canopy (fig. 58) (Boldt and Van Deusen 1974; Shepperd and Battaglia 2002). As a result, stand tending in the form of cleanings and thinnings is suggested to ensure trees develop satisfactorily to provide for a variety of uses including grazing, wildlife habitat, recreation, and timber production. Otherwise, especially with ponderosa pine and lodgepole pine stands, tree diameter growth can stagnate and dense stands of trees with small diameters can develop (Boldt et al. 1983; Myer 1938 et al.) (fig. 59). Wildfire, weather, and mountain pine beetles are natural agents that remove trees and reduce stand stocking, but their timing, precision, uncertainty, and outcomes are very indeterminate (Graham et al. 2016; Shepperd and Battaglia 2002).

Myers (1967) intended to provide information about how ponderosa pine forests throughout the Western United States developed when thinned to different stocking levels (tree densities). In 1961, his first GSL installations were started on the Black Hills Experimental Forest and Fort Valley Experimental Forest in Arizona. The GSL study in both areas was installed, treated, and measured by 1963 (Myers and Boldt 1961; Schubert 1971). Myers (1967) suggested that tree thinning frequency and intensity were sometimes constrained by only one thinning being practicable during a rotation. As a result, he intended to obtain tree and stand information over a range of structures (e.g., density, tree sizes, and volume) and site conditions with minimal operational restrictions. As a result, for each of his GSLs, the study started with more trees than desired, to allow for thinnings to reach the mean d.b.h. of 10 inches and the desired BA (i.e., 20, 40, 60, 80, 100, 120 square feet) (figs. 60, 61). Also, the highest and lowest tree densities he selected were beyond the desirable range of growing stock for all alternatives of timber production (Myers 1967).

Myers' "best" GSL of 80, which he bracketed with less and greater GSLs in the study, had a target of 147 TPA when the d.b.h. reached 10 inches and the BA reached 80 square feet (figs. 60, 61). During the course of the study, all of the GSLs in the Black Hills had minimal trees die (1963–2010), until the MPB epidemic of 2012, indicating that few extra trees were needed other than the desired number for a given GSL when the d.b.h. or QMD reached 10 inches (fig. 24). As mentioned earlier, regeneration of ponderosa pine seedlings after canopy disturbance is not an issue in the Black Hills; rather, too any trees are the norm (figs. 58, 59).

Figure 58—Eight- to 10-year-old ponderosa seedlings under an 80-year-old over story. The tree density had been reduced from about 180 square feet of basal area to about 65 square feet per acre in 1952 in the area that would become the Black Hills Experimental Forest (section 33).

Figure 59—Without disturbance, the abundant ponderosa pine regeneration that occurs in the Black Hills can remain small in diameter and in some occasions tree growth can be minimal, or in other words, stagnate.

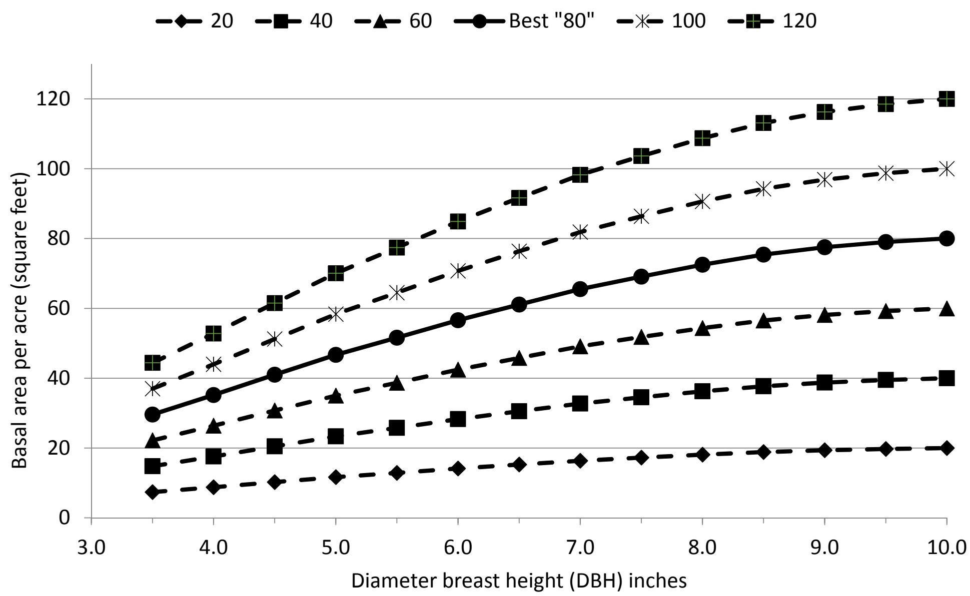


Figure 60—Using the GSL 80 (i.e., "best" basal area per acre for trees with different diameters), Meyers (1967) also tested 25 percent of GSL 80, GSL 20; 50 percent, GSL 40; 75 percent, GSL 60; 125 percent, GSL 100; and 150 percent, GSL 120.

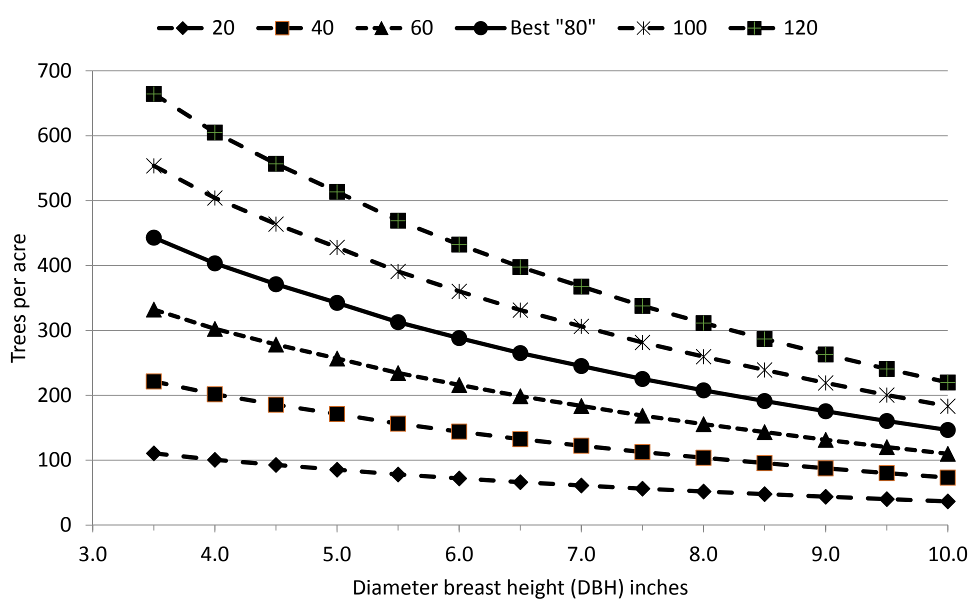


Figure 61—In addition to defining the desired basal area for each GSL and d.b.h., Meyers (1967) also provided the desired number of trees per acre for each GSL depending on d.b.h.

Myers and Boldt established both sapling and pole GSL plots in 65-year-old ponderosa pine stands on the Black Hills Experimental Forest (fig. 17). Trees on sapling plots had a QMD of 3.9 inches and trees on the pole plots had a QMD of 6.8 inches (fig. 27). Although no pretreatment TPA was recorded for the GSL plots, the unthinned sapling plots in 1978 had a mean of 858 TPA and the pole plots had a mean of 750 TPA (fig. 24). Using these data and the slope of TPA curves for the unthinned plots (fig. 24), the sapling plots when established in 1963 most likely had in excess of 1,000 TPA and the pole plots conservatively had 800 to 900 TPA. As a result, with the exception of BA, there were significant differences in both the tree and stand metrics between the plot types. Because the pole plots started with larger trees from 1963 through 2010 before the MPBs severely impacted the plots, the larger QMDs, volumes, SDIs, and other stand metrics occurred on the pole plots compared to the sapling plots.

Even though Myers (1967) planned for multiple tree thinnings in the study, through 1978 they occurred as planned but through 1998 they were very sporadic (fig. 20). Also, the pole GSL 20 and 40 quickly hit their target BA within 5 years of study initiation and the other sapling and pole GSLs reached their target BA by about 1984. As a result, the GSL concept is well founded, but it is very hard to accomplish experimentally, let alone operationally. Another shortcoming of planning for multiple thinnings from below, was that the harvested trees had little or no commercial value. For example, 350 TPA were harvested from the sapling GSL 120 plots through 1998 and all of these trees had QMDs less than 7.0 inches (unmerchantable except for fuel, posts, and poles) making their removal a cost rather than a benefit (financial) to stand management (figs. 27, 39). Similarly, 209 TPA were removed from the sapling GSL 80 plots through 1998 and possibly a few trees with 8.0 inch QMDs were removed in 1998, hardly making the thinning operation profitable (figs. 27, 39). Even though Myers (1967) suggested that more than one thinning would be desired in a rotation, the data summarized here indicate that one thinning may be preferable.

Although just an estimate, the Forest Vegetation Simulator (FVS) indicates that ponderosa pine trees in the Black Hills with QMDs of approximately 6 inches can be obtained by 40 years of age with densities of 100 to 400 TPA (Dixon 2002; Wykoff et al. 1982) (fig. 62). Similarly, trees with a QMD over 10 inches can be grown by age 65 years when the TPA is less than 200 (fig. 62). This analysis indicates that if the “best” GSL of 80 is desired, a thinning by age 30 years would be warranted to a density of approximately 200 TPA (147 TPA target when QMD is 10 inches and BA is 80 square feet) (figs. 60, 61). Of interesting note, this target of 30 years for finalizing desired stand structures and compositions for stands in the moist forests of the northern Rocky Mountains was also suggested by Graham (1988) and Bates (1919), who indicated the best time for thinning ponderosa pine trees in the Black Hills was age 20 to 25

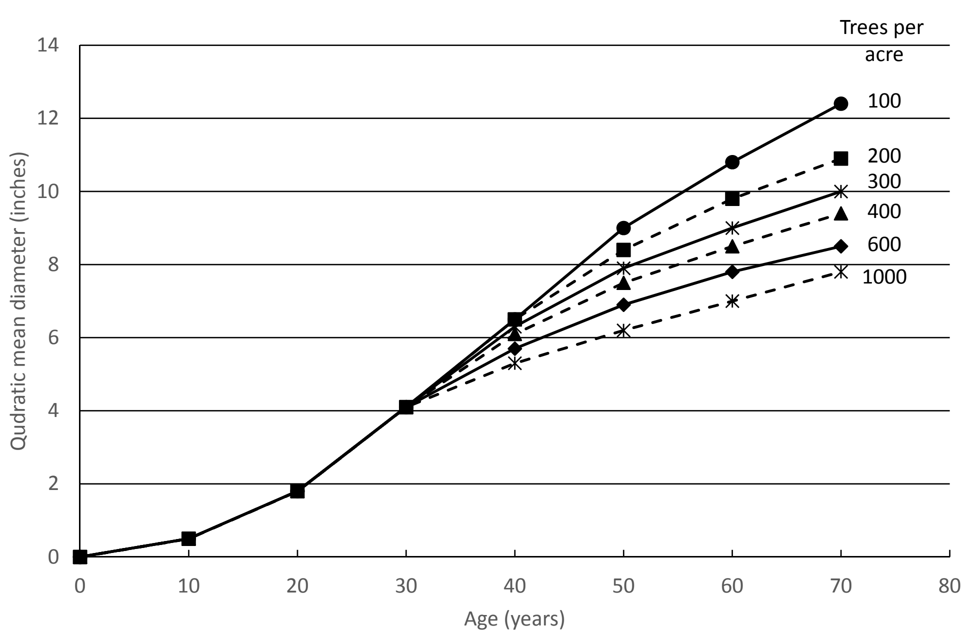


Figure 62—The Forest Vegetation Simulator (FVS) was used to show how QMDs are impacted by different tree densities of ponderosa pine trees in the Black Hills.

years. Contrary to Myers' conjecture that multiple thinnings would be desired to manage for a given GSL, one thinning (i.e., cleaning, precommercial thinning) close to the desired target TPA when the QMD is 10 inches and the desired BA for a GSL is reached appears to be warranted. The TPA targets Myers (1967) suggested for GSL 20 was 37 TPA, for GSL 40, 73 TPA; for GSL 60, 110 TPA; for GSL 80, 147 TPA; for GSL 100, 183 TPA; and for GSL 120, 220 TPA (fig. 61). These targets, how the different thinning regimes expressed by the GSL (i.e., 20 through 120) performed, and the different tree QMDs that FVS indicates are possible, provide information that can inform precommercial thinning activities (fig. 62). Roeser (1937) suggested that when production of saw logs was the objective, one precommercial thinning of ponderosa pine stands was desirable to 300 TPA when the mean d.b.h. was 5 inches.

The last thinning in the GSL plots occurred in 1998 when 100-year-old trees were removed from each GSL (figs. 20, 24). Bates (1919) indicated that ponderosa pine would respond to thinning up to 100 years of age but further study was needed and the 1998 thinnings were able to address this issue. Within each GSL after the 1998 thinnings, the residual trees significantly responded to the additional growing space (figs. 28, 29). What was remarkable is that trees in both the sapling and pole GSL 20 plots responded positively to the thinnings even though only 69 TPA producing 48 square feet of BA occurred on the sapling plots and 41 TPA and 45 square feet of BA occurred on the pole plots prior to thinning (figs. 56, 63). These exceptional growth responses to the increased growing space occurred at a mean SDI of 83 on the sapling plots and a mean SDI of 70 for the pole plots, below the SDI of 115, at which intra-tree competition theoretically commences (Long and Shaw 2005). At these densities, light does not appear to be a limiting factor for tree growth but possibly more water became available to the residual trees allowing them to increase growth rates (figs. 56, 63).

Figure 63—GSL 20 sapling plot 42 in 2004. In 2003, 5 years after it was thinned, GSL 20 plot 42 had 22 feet^2 per acre of basal area, a mean of 28 trees per acre, a QMD of 12.1 inches, an SDI of 38, 430 feet^3 per acre, 358 merchantable feet^3 per acre, and 1,560 board feet per acre.

Myers and Boldt (1961) wanted to determine the maximum volumes that could be grown on average sites in the Black Hills. The maximum volumes in the GSL study at 100 years of age occurred on the unthinned plots with the sapling plots producing 3,307 and the pole plots producing 3,945 cubic feet per acre. These volumes were very comparable to those described by Meyer (1938) of 3,400 to 3,900 cubic feet per acre for 100-year-old even-aged stands growing on sites with indexes of 50 to 60. Similarly, Long and Shaw (2005) suggested that 2,000 to 2,500 cubic feet per acre were possible for sites (figs. 64, 65) with the same indexes when their SDIs neared a maximum of 450. Similar to the pole GSL plots starting with larger trees producing trees with larger QMDs than the GSL sapling plots, the pole GSL plots produced more volume than the sapling GSL plots reinforcing the suggestion that precommercial thinnings are desired. For example, the peak total cubic volume of the sapling GSL 120 plots was 2,532 cubic feet per acre and the pole GSL 120 plots for the same time had 3,273 cubic feet per acre (fig. 35). Also, these volumes of the GSL 120 plots in both respective plot groups were similar to the volumes that occurred on the unthinned plots. The QMDs of the trees on unthinned sapling plots (7.1 inches) at age 100 were similar to those occurring on the GSL 120 plots (7.6 inches). However, the QMDs of trees on the GSL pole 120 plots (9.4 inches) were significantly larger than those of trees on the unthinned pole plots (7.3 inches) at age 100 (figs. 27, 35). These outcomes suggest that even modest amounts of thinning produced tree sizes that potentially had more value than those occurring in areas not thinned.

Thinning redistributes the volume a site can produce to fewer trees, thus not increasing the volume a site can produce but, rather making the volume more valuable is hardly a new concept (Bates 1919; Krueger 1936; Stage 1958). Nevertheless, the GSL study refined these relationships for low productivity ponderosa stands such as those occurring in the Black Hills. For the sapling plots, the GSL 80 plots produced more merchantable volume than any of the other sapling GSL plots (figs. 36, 66). Two significant groups of merchantable cubic volumes occurred within the pole GSL plots. With merchantable mean cubic feet volumes in 2010 ranging from 2,134 to 2,345 cubic feet per acre, the pole GSLs 80, 100, and 120 produced the most volume from years 1963 through 2010.

Figure 64—In 2003, unthinned sapling plot 21 had 177 feet^2 per acre of basal area, 628 trees per acre, a QMD of 7.1 inches, an SDI of 369, 3,689 feet^3 per acre, 1,750 merchantable feet^3 per acre, and 9,240 board feet per acre.

Figure 65—In 2003, unthinned pole plot 72 had 185 feet^2 per acre of basal area, 668 trees per acre, a QMD of 7.1 inches, an SDI of 388, 3,419 feet^3 per acre, 715 merchantable feet^3 per acre, and 3,560 board feet per acre.

Figure 66—In 2003, the sapling GSL 80 plot 35 had 88 feet^2 per acre of basal area, 140 trees per acre, a QMD of 10.7 inches, an SDI of 157, 1,944 feet^3 per acre, 1,538 merchantable feet^3 per acre, and 7,040 board feet per acre.

The other group of similar merchantable cubic means included pole GSL 40 and 60 with the year 2010 means being 1,615 merchantable cubic per acre for GSL 60 and 1,193 merchantable cubic feet per acre for the GSL 40 plots. Similar results were found for the production of Scribner board feet with the sapling GSL 80 plots producing 9,107 board feet and the pole GSL 80 plots producing 10,253 board feet per acre in 2010 when the plots were age 112 years (fig. 67). In respect to producing merchantable volumes in the Black Hills, these data suggest that the thinning regimes displayed by the "best" GSL 80 for both the sapling-sized and pole-sized trees appear to offer excellent opportunities for merchantable volume production on trees with QMDs ranging from 11.2 to 12.7 inches (figs. 27, 36, 37, 66, 67).

As important to producing commercially viable volumes per acre is the diameter of the trees in which the volume is contained. The default merchantable specification for ponderosa pine trees growing in the Black Hills within the FVS was a 9.0 inch QMD and 6.0 inch top (Keyser and Dixon 2008). However, locally and depending on log prices, merchantability tree specifications may differ. As such, it becomes a balance in producing merchantable volumes and tree QMD. The 10,253 board feet produced by the pole GSL 80 thinning regime was contained in trees with a QMD of 12.7 inches, a very respectable merchantable sized tree (fig. 67). Also, because of the thinnings that occurred from 1963 through 2010, there was minimal variation in this mean as the standard error was 0.44 inches, indicating that 68 percent of the QMDs ranged from 12.3 to 13.1 inches. This finding also reinforces the necessity of cleaning (precommercial thinning) ponderosa pine stands in the Black Hills by age 30 years if such tree sizes and volumes are to be produced (figs. 62, 66, 67).

Figure 67—In 2003, pole GSL 80 plot 62 had 98 feet^2 per acre of basal area, mean of 128 trees per acre, a QMD of 12.1 inches, an SDI of 142, 2,056 feet^3 per acre, 1,747 merchantable feet^3 per acre, and 8,080 board feet per acre.

Myers (1967) purposely chose GSLs to be above and below what would be the norm (e.g., best) for stand structures to produce commercial volumes and sized trees. As a result, the GSL plots do an excellent job of displaying the forest productivity that can be expected at different stocking levels, tree ages, and tree densities. The thinnings that occurred in both the sapling and pole GSL 20 plots over the years show the productivity of site index 55 to 60 ponderosa pine stands when tree densities ranged from 8 to 48 square feet of BA and QMDs ranged 3.9 to 14.3 (figs. 27, 55). In 1968, 5 years after the plots were established, the sapling plots had a periodic annual cubic foot increment (PAI-CF) of 9.5 cubic feet per acre per year and the pole GSL plots had a PAI-CF of 18.2 cubic feet per acre per year for the same time period (fig. 55).

At age 100 years in 1998, the sapling GSL 20 plots had a PAI-CF of 36.3 and the pole GSL 20 plots had a PAI-CF of 29.1 cubic feet per acre per year when both of their BA densities were the greatest. The overall mean PAI-CF from 1963 through 2010 for the sapling GSL 20 plots was 25.0 cubic feet per acre per year and the mean PAI-CF for the pole GSL 20 plots was 23.1 cubic feet per acre per year (fig. 54). As a result, the PAI-CFs resulting from the thinning regimes of the GSL 20 plots were near the 20 cubic feet per acre per year threshold that defines a commercial forest (Day 1981; Clawsen 2016; USDA 1969, 1992).

Day (1981) suggested that Western timberlands supporting ponderosa and lodgepole pine would usually require productivity rates of 100 cubic feet per acre per year or more to be judged commercial. None of the mean productivity rates of any GSL from 1963 through 2010 met this 100 cubic feet per acre per year threshold. The maximum sapling GSL 80 plots had a PAI-CF of 61.3 and the pole GSL 80 plots had a PAI-CF of 56.3 cubic feet per acre per year, both being maximum for their respective plot group (fig. 54). The maximum PAI-CF observed in both plot groups occurred for the 2003 to 2006 period when the trees on the plots were 108 years old. The sapling GSL 120 plots had a PAI-CF of 97.1 and the pole GSL 120 plots had a PAI-CF of 85.3 cubic feet per acre per year (fig. 55). Maximum values of this magnitude only occurred during this period and were less than the 100 cubic feet per acre per year that Day (1981) suggested was the minimum for a commercial ponderosa pine forest.

These findings suggest how marginal these managed sites in the Black Hills are for meeting the minimums for the definition of a commercial forest. Also, the GSL 20 and 40 plots very likely represent many of the current stand structures across the central Hills that were impacted by the recent epidemic of mountain pine beetles (Graham et al. 2016).

Concluding Remarks

Forest tending to produce desired tree sizes dates to at least the mid-17th century, as Evelyn (1664) described forest treatments for the production of ship masts. Schlich (1904) provided the modern concepts of tree thinning to produce desired stand volumes and tree sizes. As a result, with this long history of forest tending worldwide, what new, complementary, or added knowledge could the growing stock level study Myers (1967) started in 1961 add to the body of work? Much complementary and additive knowledge was added on traditional thinning responses such as merchantable volume produced, importance of reducing tree density to increase QMDs, and suggested thinning regimes to produce a variety of QMDs and volumes. Most importantly, these and similar studies and data can inform forest management and policy actions that can be developed to produce wildlife habitat, protect watersheds, treat fuels, and other vegetative treatments that may arise in the future.

The finding that at low densities (e.g., 40 square feet of BA) of 100-year-old ponderosa pine trees could significantly respond to increased growing space following the 1998 thinning was unexpected and very relevant for informing the timing and age at which thinning ponderosa pine stands responds to tree density changes. The trees located on the GSL 20 plots had a 146 percent increase in basal area increment after thinning and trees on the GSL 20 sapling plots had a 123 percent response to the thinning (fig. 28). In fact, trees in all of the GSL plots had a significant response to the 1998 thinnings, with several exceeding 200 percent. Most likely these responses were related to the increase in available water and less to an increase in available light.

There are several concepts over the years that have been developed for informing stand tending goals and methodologies. These include growth basal area, crown competition factor, stand density index, and growing stock level as described in this study (Hall 1983; Krajicek et al. 1961; Long and Shaw 2005; Myers 1967; Reineke 1933). All of these aids have value but one of their main weaknesses is how the treatments get completed to produce the desired outcomes. Myers (1967) produced elegant TPA and BA suggestions, depending on d.b.h., to produce a 10 inch d.b.h. tree while simultaneously reaching BA targets of 20, 40, 60, 80, 100, and 120 square feet. It is a very good concept, but even experimentally on small plots (i.e., 0.25 and 0.50 acres), it could not be accomplished, illustrating how difficult it would be to complete at the stand and multiple stand levels.

Multiple thinnings to produce desired tree and stand characteristics are very appropriate for high productive forests where there is a market for the wood removed during intermediate thinnings (Kline and Coleman 2010; Susaeta et al. 2009). However, on the minimally commercial growing sites in the Black Hills, multiple thinnings that have no commercial value only add to the financial uncertainties of growing commercial forests in the Black Hills. Myers (1967) did provide excellent TPA suggestions for producing a tree with a 10 inch d.b.h. when a desired BA is achieved. Instead of using multiple thinnings to achieve these targets, one precommercial thinning near the final desired TPA for a 10-inch tree and given BA may be preferred since too much regeneration is the norm in the Black Hills.

Even though elegant prescriptions such as Myers produced offer multiple alternatives for managing contemporary forests, nature has a way of interrupting and even making such prescriptions moot. For 48 years, the GSL concept was used to manage plots on the Black Hills Experimental Forest with some difficulty. However, this study revealed many options for producing high-quality trees and stands of timber. Within 2 years, all of the work and impressive results were taken away by mountain pine beetles (MPBs). Every plot, even those with tree densities (e.g., 50 to 70 square feet of BA) that Graham et al. (2016) suggested were resistant to MPBs, were heavily impacted by MPBs. As a result, the study that Myers and Boldt precisely started and the thousands of person-days over decades that were used to maintain and monitor the plots were lost to MPBs. Even with this result, forest densities ranging from 40 to 80 square feet per acre of BA still appear to be a reasonable target for offering some resilience and resistance of ponderosa pine forests from epidemic MPBs and unwanted wildfires (Graham et al. 2015, 2016).

The objective of forestry research is to discover and develop knowledge to inform management actions and increase the understanding of how forests develop. Such work cannot be accomplished if it wasn't for people like Cliff Myers and Chuck Boldt who installed a well thought out replicated study in 1961. Such long-term studies and their protection and maintenance, in this case for over 55 years, are invaluable to solving and informing contemporary forest management issues. Even though this GSL installation was lost to the largest mountain pine beetle epidemic to strike the Black Hills in the last century, others are still being monitored in the Western United States carrying on the legacy of Forest Service Research.

References

Alexander, Robert R.; Edminster, Carlton B. 1981. Management of ponderosa pine in even-aged stands in the Black Hills. Res. Pap. RM-228. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 10 p.

Avery, T. Eugene. 1967. Forest measurements. New York: McGraw-Hill. 290 p.

Barnes, Burton V.; Zak, Donald R.; Denton, Shirley R.; [et al.]. 1998. Forest ecology. 4th ed. New York: John Wiley and Sons. 774 p.

Bates, C.G. 1919. Effects of thinning in Black Hills yellow pine. Progress report for 1919. Unpublished paper on file with: U.S. Department of Agriculture, Forest Service, Forestry Sciences Laboratory, Moscow, ID. 46 p.

Boldt, Charles E. 1971. Stocking and growth in even-aged forest stands: A simple, instructional model. Proceedings of the South Dakota Academy of Science. 50: 79–84.

Boldt, Charles. E.; Alexander, Robert R.; Larson, Milo J. 1983. Interior ponderosa pine in the Black Hills. In: Burns, Russell M., tech. comp. Silvicultural systems for the major forest types of the United States. Agric. Handb. 445. Washington, DC: U.S. Department of Agriculture, Forest Service: 80–83.

Boldt, Charles E.; Van Deusen, James L. 1974. Silviculture of ponderosa pine in the Black Hills: The status of our knowledge. Res. Pap. RM-RP-124. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 45 p.

Clawson, Marion. 2016. Forest policy for the future: Conflict compromise, consensus. New York: Routledge. 370 p.

Clow, Richmond L. 1998. Timber users, timber savers: Homestake Mining Company and the first regulated timber harvest. Forest History Today. 4(1): 6–11.

Cochran, H.D. 1939. What price thinning and what value. Journal of Forestry. 37(8): 659–660.

Day, Robert D., Jr. 1981. “Commercial timberland”—A misnomer. Journal of Forestry. 79(1): 6.

Dilworth, J.R.; Bell, J.F. 1985. Log scaling and timber cruising. Corvallis, OR: OSU Bookstores. 468 p.

Dixon, Gary E. 2002. Essential FVS: A user’s guide to the Forest Vegetation Simulator. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 196 p.

Edminster, Carleton B. 1988. Stand density and stocking in even-aged ponderosa pine stands. In: Baumgartner, David M.; Lotan, James E., eds. Ponderosa pine: The species and its management: Symposium proceedings; 1987 September 29–October 1; Pullman, WA. Spokane, WA: Washington State University: 253–260.

Egan, Timothy 2009. The big burn: Teddy Roosevelt and the fire that saved America. New York: Houghton Mifflin Harcourt. 324 p.

Ensz, Edgar H. 1990. Soil survey of Custer and Pennington Counties, Black Hills parts, South Dakota. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service. 295 p.

Evelyn, John. 1664. Sylva, or a discourse of forest-trees, and the prorogation of timber in his majesties dominions. London: Royal Society. 83 p.

Freeman, John F. 2015. Black Hills forestry: A history. Boulder, CO: University Press of Colorado. 246 p.

Gaines, Edward M.; Kotok, E.S. 1954. Thinning ponderosa pine in the southwest. Stn. Pap. 17. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 20 p.

Graham, Russell T. 1988. Influence of stand density on western white pine, redcedar, hemlock, and grand fir in the northern Rocky Mountains. In: Schmidt, Wynan C., comp. Proceedings—Future forests of the Mountain West: A stand culture symposium; 1986 September 29–October 3; Missoula, MT. Gen. Tech. Rep. INT-243. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 175–184.

Graham, Russell T.; Bayard de Volo, Shelley; Reynolds, Richard T. 2015. Northern goshawk and its prey in the Black Hills: Habitat assessment. Gen. Tech. Rep. RMRS-GTR-339. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 177 p.

Graham, Russell T.; Asherin, Lance A.; Battaglia, Michael A.; [et al.]. 2016. Mountain pine beetles: A century of knowledge, control attempts, and impacts central to the Black Hills. Gen. Tech. Rep. RMRS-GTR-353. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 193 p.

Haig, Irving T. 1932. Second-growth yield, stand, and volume tables for the western white pine type. Tech. Bull. 323. Washington, DC: U.S. Department of Agriculture. 67 p.

Hall, Frederick C. 1983. Growth basal area: A field method for appraising forest site potential for stockability. Canadian Journal of Forest Research. 13(1): 70–77.

Harmon, Wendell H. 1955. Ponderosa pine management in the Black Hills. Ames Forester. 42: 6–8.

Harris, J.L., comp. 2013. 2012 Forest insect and disease conditions, Rocky Mountain Region (R2). Golden, CO: U.S. Department of Agriculture, Forest Service. 68 p.

Hoffman, G.R.; Alexander, R.R. 1987. Forest vegetation of the Black Hills National Forest of South Dakota and Wyoming: A habitat type classification. Res. Pap. RM-RP-276. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 48 p.

Hornibrook, E.M. 1936. Some results of thinning in small pole stands of ponderosa pine in the Southwest. Journal of Forestry. 34(9): 862–866.

Kenward, Michael G.; Roger, James H. 1997. Small sample inference for fixed effects from restricted maximum likelihood. Biometrics. 53(3): 983–997.

Keyser, Chad E.; Dixon, Gary E., comps. 2008 (revised 2015). Central Rockies (CR) variant overview—Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 75 p.

Kline, Keith L.; Coleman, Mark D. 2010. Woody energy crops in the southeastern United States: Two centuries of practitioner experience. Biomass and Bioenergy. 34(12): 1655–1666.

Krajicek, John E.; Brinkman, Kenneth A.; Gingrich, Samuel F. 1961. Crown competition—A measure of density. Forest Science. 7(1):35–42.

Kramer, Clyde Young. 1956. Extension of multiple range tests to group means with unequal numbers of replications. Biometrics. 12(3): 307–310.

Krauch, Hermann. 1949. Results of thinning experiment in ponderosa pine pole stands in central Arizona. Journal of Forestry. 47(6): 466–469.

Krueger, Theodore. 1936. Timber stand improvement work in the Black Hills. Journal of Forestry. 34(6): 609–612.

Langsaeter, A. 1941. Omtynning i analdret granfurvskog Maddel. Norsite Skogfor Soksvenson. 8: 131–216.

Long, J.N. 1985. A practical approach to density management. The Forestry Chronicle. 61(1): 23–27.

Long, James N.; Shaw, John D. 2005. A density management diagram for even-aged ponderosa pine stands. Western Journal of Applied Forestry. 20(4): 205–215.

Long, James N.; Smith, Frederick W. 1984. Relation between size and density in developing stands: A description and possible mechanisms. Forest Ecology and Management. 7(3): 191–206.

McArdle Richard E.; Meyer, Walter H. 1930. The yield of Douglas-fir in the Pacific Northwest. Tech. Bull. 201. Washington, DC: U.S. Department of Agriculture. 64 p.

Meyer, Walter H. 1934. Growth in selectively cut ponderosa pine forests of the Pacific Northwest. Tech. Bull. 407. Washington, DC: U.S. Department of Agriculture. 64 p.

Meyer, Walter H. 1937. Yield of even-aged stands of sitka spruce and western hemlock. Tech. Bull. 544. Washington, DC: U.S. Department of Agriculture. 86 p.

Meyer, Walter H. 1938. Yield of even-aged stands of ponderosa pine. Tech. Bull. 630. Washington, DC: U.S. Department of Agriculture. 60 p.

Myers, Clifford A. 1958. Thinning improves development of young stands of ponderosa pine in the Black Hills. Journal of Forestry. 56(9): 656-659.

Myers, Clifford A. 1967. Growing stock levels in even-aged ponderosa pine. Res. Pap. RM-33. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 8 p.

Myers, Clifford A.; Boldt, Charles E. 1961. Growing stock levels for Black Hills ponderosa pine. Study Plan. Rapid City, SD: Rocky Mountain Forest and Range Experiment Station. Unpublished paper on file with: U.S. Department of Agriculture, Forest Service, Forestry Sciences Laboratory, Moscow, ID. 82 p.

Myers, Clifford A.; Van Deusen, James L. 1960a. Natural thinning of ponderosa pine in the Black Hills. Journal of Forestry. 58(12): 962–964.

Myers, Clifford A.; Van Deusen, James L. 1960b. Site index of ponderosa pine in the Black Hills from soil and topography. Journal of Forestry. 58(7): 548–555.

Oliver, William W. 2005. The west-wide ponderosa pine levels-of-growing-stock study at age 40. In: Ritchie, Martin W.; Maguire, Douglas A.; Youngblood, Andrew, tech. coords. Proceedings of the symposium on ponderosa pine: Issues, trends, and management; 2004 October 18–21; Klamath Falls, OR. Gen. Tech. Rep. PSW-GTR-198. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 71–80.

Oliver, William W.; Ryker Russell A. 1990. Pinus ponderosa (Dougl. Ex. Laws.): Ponderosa pine. In: Burns, Russell M.; Honkala, Barbara H., tech. coords. Silvics of North America: Volume 1 - Conifers. Agric. Handb. 654. Washington, DC: U.S. Department of Agriculture, Forest Service: 413–424.

Pearson, G.A. 1935. Timber stand improvement in the southwest. Journal of Forestry. 33(2): 128–132.

Pearson, G.A. 1936. A thinning experiment applied to timber stand improvement. Journal of Forestry. 34(9): 855–861.

Pearson, G.A. 1944. Thinnings in ponderosa pine. Journal of Forestry. 42(8): 608–609.

Pearson, G.A. 1950. Management of ponderosa pine in the Southwest: As developed by research and experimental practice. Agric. Monograph 6. Washington, DC: U.S. Department of Agriculture, Forest Service. 218 p.

Pinchot, Gifford; Graves, Henry S. 1896. The white pine: A study with tables of volume and yield. New York: Century Company. 102 p.

Potter, Kevin M.; Hipkins, Valerie D.; Mahalovich, Mary F.; [et al.]. 2013. Mitochondrial DNA haplotype distribution patterns in *Pinus ponderosa* (Pinaceae): Range-wide evolutionary history and implications for conservation. American Journal of Botany. 100(8): 1562–1579.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research. 46(7): 627–638.

Roeser, J., Jr. 1937. The role of timber stand improvement in the Black Hills. Black Hills Engineer. 24(1): 48–54.

Roth, Filbert. 1925. Forest regulation or the preparation and development of forest working plans. Ann Arbor, MI: George Waher Publishing. 239 p.

Ruppert, David; Wand, M.P.; Carroll, R.J. 2003. Semiparametric regression. Cambridge Series in Statistical and Probabilistic Mathematics. No. 12. Cambridge, England: Cambridge University Press. 386 p.

Sanders, Peggy. 2004. The Civilian Conservation Corps in and around the Black Hills. Chicago, IL: Arcadia Publishing. 128 p.

Schlich, W. 1904. Schlich's manual of forestry, Volume II. Silviculture. 3rd ed. London: Bradbury, Agnew and Company. 393 p.

Schubert, Gilbert H. 1971. Growth response of even-aged ponderosa pine related to stand density levels in Arizona. Journal of Forestry. 69(12): 857–860.

Severson, Keith E.; Boldt, Charles E. 1977. Options for Black Hills forest owners: Timber, forage, or both. Rangeman's Journal. 4(1):13–15.

Shepperd, Wayne D.; Battaglia, Michael A. 2002. Ecology, silviculture, and management of Black Hills ponderosa pine. Gen. Tech. Rep. RMRS-GTR-97. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 112 p.

Six, D.L.; Paine, T.D. 1998. Effects of mycangial fungi and host tree species on progeny survival and emergence of *Dendroctonus ponderosae* (Coleoptera: Scolytidae). Environmental Entomology. 27(6): 1393–1401.

Smith, David Martyn. 1962. The practice of silviculture. New York: John Wiley and Sons. 578 p.

Stage, A.R. 1958. Growth of thinned ponderosa pine in western Montana. Journal of Forestry. 56(10): 757–760.

Stickel, P.W.; Hawley, R.C. 1924. Comparative basal areas. Journal of Forestry. 22(3): 302–305.

Stuart, E., Jr.; Roser, J., Jr. 1944. Effect of thinning in the Black Hills. Journal of Forestry. 42(4): 279–280.

Susaeta, Andres; Alavalapati, Janaki R.R.; Carter, Douglas R. 2009. Modeling impacts of bioenergy markets on nonindustrial private forest management in the southeastern United States. Natural Resource Modeling. 22(3): 345–369.

U. S. Department of Agriculture. 1969. A progress report on the western-wide study of the classification of commercial forest land. Unpublished report on file with: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT. 27 p.

Van Hooser, Dwane; Keegan, Charles E., III. 1988. Distributions and volumes of ponderosa pine forests. In: Baumgartner, David M.; Lotan, James E., eds. Ponderosa pine: The species and its management; Symposium proceedings; 1987 September 29–October 1; Spokane, WA. Pullman, WA: Washington State University: 1–6.

Walters, Brian F.; Woodall, Christopher W.; Piva, Ronald J.; [et al.]. 2013. Forests of the Black Hills National Forest 2011. Resour. Bull. NRS-83. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 36 p.

Western Regional Climate Center. Page last modified: 2011 April. Rochford 2 WNW, South Dakota (397227), Period of Record Monthly Climate Summary: 10/01/1897 to 09/24/2006. Reno, NV: Western Regional Climate Center. https://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?sd7227 [Accessed 2017 October 29].

White, Halbert. 1982. Maximum likelihood estimation of misspecified models. Econometrica. 50(1): 1–25.

Wykoff, William, R.; Crookston, Nick L.; Stage, Albert R. 1982. User's guide to the stand prognosis model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 112 p.

Appendix A—Summary of the Analyses for Each Response Variable

A Generalized Linear Mixed Model (GLMM) was used to analyze all responses. The predictors include GSL, pole or sapling, year, thinning, and the GSL by pole or sapling interactions. The models incorporated a log-link function in order to account for nonnegative response distributions. A repeated measures temporal correlation structure was incorporated into all models using a radial smoother for each plot (Ruppert et al. 2003). Treatment-level comparisons between main and interaction fixed-effect levels were adjusted using Tukey's method determined using least squares means (Kramer 1956). Degrees of freedom were adjusted using the Kenward-Roger method (Kenward and Roger 1997). When necessary, an empirical sandwich covariance estimator was included in order to account for over dispersion (White 1982). All analyses were conducted using SAS PROC GLMMIX in Version 9.4 of the SAS System for Windows (Copyright © 2014 SAS Institute Inc.). Where appropriate, two analysis tables are presented. One was created for the years 1963 through 2010 that did not include the unthinned plots, and a separate analysis was conducted for the years 1978 through 2010 that included data from the unthinned plots. As a result, the significant grouping of similar least squares means were for the entire years of record and not just for any one given year.

Table A1—The analysis of variance table for trees per acre. These data are displayed in figure 24 in the main text in RMRS-GTR-393.

Years 1963 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	5	234.87	<0.0001
Sapling/pole[b]	1	280.41	<0.0001
Sapling/pole*year[c]	5	0.55	0.7393
GSL*year[d]	50	3.96	<0.0001
Year	10	83.07	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Years 1978 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	282.43	<0.0001
Sapling/pole[b]	1	116.30	<0.0001
Sapling/pole*year[c]	6	15.45	<0.0001
GSL*year[d]	30	11.02	<0.0001
Year	5	110.72	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate the trees per acre among the GSL from 1963 through 2010 and 1978 through 2010 when the unthinned plots were included. In the following table the true trees per acre means for 2010 are shown along with the standard error of the mean.

Trees per acre least squares means								**2010 true values**	
	t value	**Pr > |t|**	**LS**	**Std**	**95% conf. limits**		**Sig.**	**Mean**	**Std.**
Sapling GSL			**mean**	**error**	**lower**	**upper**	**diff.**		**error**
20 sapling	59.5	<0.0001	51.1	3.37	44.8	58.2	a	24.0	2.31
40 sapling	87.1	<0.0001	114.5	6.23	102.7	127.6	b	60.0	1.00
60 sapling	99.5	<0.0001	182.6	9.55	164.5	202.6	c	106.7	9.33
80 sapling	107.2	<0.0001	251.6	12.98	227.0	278.8	d	153.3	14.11
100 sapling	112.7	<0.0001	319.4	16.34	288.4	353.7	e	224.0	15.14
120 sapling	117.9	<0.0001	404.7	20.60	365.6	447.9	f	86.7	11.39
UnThin sap	116.3	<0.0001	496.1	26.47	446.0	551.8	g	462.7	38.94
Pole GSL									
20 pole	46.9	<0.0001	31.1	2.28	26.9	35.9	A	15.3	1.33
40 pole	78.2	<0.0001	76.9	4.28	68.9	85.9	B	46.0	2.00
60 pole	91.4	<0.0001	124.1	6.55	111.7	137.8	C	76.7	3.71
80 pole	98.5	<0.0001	165.5	8.58	149.2	183.5	D	111.3	8.35
100 pole	105.7	<0.0001	226.5	11.6	204.5	250.9	E	157.3	29.67
120 pole	109.8	<0.0001	271.9	13.88	245.6	301.0	F	191.3	30.60
UnThin pole	119.9	<0.0001	598.8	31.92	538.4	665.9	G	505.3	82.80

Table A2—The analysis of variance table for stand density index (SDI). These data are displayed in figure 25 in the main text in this volume RMRS-GTR-393.

Years 1963 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	5	227.09	<0.0001
Sapling/pole[b]	1	5.11	0.0255
Sapling/pole*year[c]	5	1.53	0.1839
GSL*year[d]	50	10.25	<0.0001
Year	10	234.09	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Years 1978 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	366.70	<.0001
Sapling/pole[b]	1	6.15	0.0141
Sapling/pole*year[c]	6	11.87	<.0001
GSL*year[d]	30	12.77	<.0001
Year	5	130.84	<.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate the stand density index (SDI) among the GSL from 1963 through 2010 and 1978 through 2010 when the unthinned plots were included. In the following table the true SDI means for 2010 are shown along with the standard error of the mean.

Stand density index (SDI) least squares means								**2010 true values**	
	t value	**Pr > |t|**	**LS**	**Std**	**95% conf. limits**		**Sig.**	**Mean**	**Std.**
Sapling GSL			**mean**	**error**	**lower**	**upper**	**diff.**		**error**
20 sapling	82.9	<0.0001	47.5	2.21	43.3	52.0	e	45	1.53
40 sapling	105.0	<0.0001	98.5	4.31	90.3	107.4	d	96	1.86
60 sapling	113.9	<0.0001	135.9	5.86	124.8	148.1	c	129	3.21
80 sapling	119.1	<0.0001	165.7	7.11	152.1	180.4	bc	182	5.21
100 sapling	122.5	<0.0001	188.7	8.07	173.4	205.4	ab	216	4.67
120 sapling	126.9	<0.0001	224.5	9.57	206.2	244.2	a	247	17.23
UnThin sap	71.6	<0.0001	294.5	8.72	277.4	312.7	f	307	4.04
Pole GSL									
20 pole	81.8	<0.0001	45.4	2.12	41.4	49.8	E	38	1.53
40 pole	101.8	<0.0001	86.6	3.80	79.4	94.4	D	84	2.65
60 pole	112.7	<0.0001	129.4	5.58	118.7	140.9	C	124	1.20
80 pole	118.3	<0.0001	160.4	6.88	147.3	174.7	B	162	3.00
100 pole	123.5	<0.0001	196.7	8.41	180.7	214.1	A	195	12.86
120 pole	126.2	<0.0001	217.3	9.27	199.7	236.5	A	217	21.36
UnThin pole	72.8	<0.0001	363.5	10.67	342.6	385.7	F	327	28.15

Table A3—The analysis of variance table for stand basal area per acre. These data are displayed in the main text in figure 26 in RMRS-GTR-393.

Years 1963 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	5	140.20	<.0001
Sapling/pole[b]	1	5.37	0.022
Sapling/pole*year[c]	5	1.62	0.158
GSL*year[d]	50	11.03	<.0001
Year	10	250.07	<.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Years 1978 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	273.60	<0.0001
Sapling/pole[b]	1	2.72	0.037
Sapling/pole*year[c]	6	7.04	<0.0001
GSL*year[d]	30	10.49	<0.0001
Year	5	118.63	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate the basal area per acre among the GSL from 1963 through 2010 and 1978 through 2010 when the unthinned plots were included. In the following table the true basal area per acre means for 2010 are shown along with the standard error of the mean.

Basal area per acre least squares means (square feet per acre)								2010 true values	
	t value	Pr > |t|	LS	Std	95% conf. limits		Sig.	Mean	Std.
Sapling GSL			mean	error	lower	upper	diff.		error
20 sapling	59.50	<0.0001	24.7	1.33	22.2	27.5	f	29.0	0.58
40 sapling	76.20	<0.0001	50.4	2.59	45.5	55.8	e	59.0	1.00
60 sapling	82.77	<0.0001	67.7	3.44	61.2	74.8	d	81.7	1.45
80 sapling	86.49	<0.0001	80.5	4.08	72.8	89.0	cd	103.3	1.45
100 sapling	88.71	<0.0001	89.2	4.51	80.7	98.6	abc	117.7	1.20
120 sapling	92.06	<0.0001	104.6	5.29	94.7	115.7	ab	131.3	10.37
UnThin sap	157.63	<0.0001	140.9	4.42	132.3	150.0	a	151.7	2.19
Pole GSL									
20 pole	60.80	<0.0001	26.4	1.42	23.8	29.4	E	26.0	1.00
40 pole	74.84	<0.0001	47.4	2.44	42.8	52.5	D	53.0	1.15
60 pole	83.32	<0.0001	69.7	3.55	63.0	77.1	C	76.0	0.98
80 pole	87.63	<0.0001	85.3	4.33	77.1	94.3	BC	97.0	0.58
100 pole	91.49	<0.0001	102.4	5.18	92.7	113.2	AB	112.7	4.37
120 pole	93.32	<0.0001	111.4	5.63	100.8	123.1	A	122.3	10.84
UnThin pole	166.65	<0.0001	175.8	5.45	165.2	187.1	F	161.0	10.58

Table A4—The analysis of variance table for quadratic mean diameter (QMD). These data are displayed in figure 27 in the main text in this volume, RMRS-GTR-393.

Years 1963 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	5	17.86	<0.0001
Sapling/pole[b]	1	385.14	<0.0001
Sapling/pole*year[c]	5	2.09	0.0687
GSL*year[d]	50	0.88	0.6978
Year	10	206.09	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Years 1978 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	62.38	<0.0001
Sapling/pole[b]	1	325.07	<0.0001
Sapling/pole*year[c]	6	7.34	<0.0001
GSL*year[d]	30	1.89	0.006
Year	5	137.93	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate the quadratic mean diameter (QMD) among the GSL from 1963 through 2010 and 1978 through 2010 when the unthinned plots were included. In the following table the true QMD for 2010 are shown along with the standard error of the mean.

Quadratic mean diameter (QMD) least squares means (inches)								**2010 true values**	
	t value	**Pr > |t|**	**LS**	**Std**	**95% conf. limits**		**Sig.**	**Mean**	**Std.**
Sapling GSL			**mean**	**error**	**lower**	**upper**	**diff.**		**error**
20 sapling	73.30	<0.0001	8.8	0.26	8.3	9.3	ab	15.0	0.64
40 sapling	72.11	<0.0001	8.5	0.25	8.0	9.0	abc	13.4	0.13
60 sapling	69.66	<0.0001	7.9	0.24	7.5	8.4	cde	11.9	0.56
80 sapling	67.53	<0.0001	7.4	0.22	7.0	7.9	efg	11.2	0.44
100 sapling	65.44	<0.0001	7.0	0.21	6.6	7.4	fg	9.8	0.29
120 sapling	64.06	<0.0001	6.7	0.20	6.3	7.1	gh	9.3	0.35
UnThin sap	71.56	<0.0001	7.1	0.196	6.766	7.542	h	7.7	0.33
Pole GSL									
20 pole	83.28	<0.0001	11.8321	0.3511	11.159	12.5459	A	17.7	0.69
40 pole	77.87	<0.0001	10.0897	0.2995	9.5155	10.6987	B	14.5	0.20
60 pole	76.57	<0.0001	9.7127	0.2884	9.1597	10.299	BC	13.5	0.31
80 pole	75.4	<0.0001	9.3869	0.2788	8.8523	9.9537	BC	12.7	0.44
100 pole	73.38	<0.0001	8.8489	0.2629	8.3448	9.3835	BCD	11.7	0.90
120 pole	72.11	<0.0001	8.5246	0.2533	8.0388	9.0397	CDE	10.9	0.49
UnThin pole	72.81	<0.0001	7.4365	0.2030	7.001	7.804	F	7.8	0.48

Table A5—The analysis of variance table for pre and post basal area increment response to the 1998 thinning treatments. These data are displayed in figure 28 in the main text in this volume, RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	5	68.65	<.0001
Sapling/pole[b]	1	18.73	<.0001
Thinning[c]	1	398.32	<.0001
GSL*sapling/pole*thinning[d]	16	0.76	0.7151

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Thinning = effect testing difference between tree growth before and after thinning.
[d]GSL*sapling/pole*thinning = effect testing interaction between GSL and measurement year.

Periodic mean annual tree basal area growth (square feet) thinning response. Pre-growth equals age 95 to 100 years and post growth equals age 105 to 112 years								True values	
GSL pre and post thinning	t value	Pr > |t|	LS mean	Std error	95% conf. limits lower	95% conf. limits upper	Sig. diff.	Mean	Std. error
Sapling GSL									
20: pre	-45.01	<0.0001	0.019	0.0017	0.016	0.023	A	0.0192	0.0006
20: post	-38.25	<0.0001	0.042	0.0035	0.036	0.051	B	0.0430	0.0053
40: pre	-45.75	<0.0001	0.014	0.0013	0.012	0.017	A	0.0140	0.0006
40: post	-41.11	<0.0001	0.032	0.0027	0.027	0.039	B	0.0322	0.0011
60: pre	-43.23	<0.0001	0.009	0.0010	0.007	0.011	A	0.0088	0.0011
60: post	-43.63	<0.0001	0.023	0.0020	0.020	0.028	B	0.0238	0.0034
80: pre	-41.25	<0.0001	0.007	0.0009	0.006	0.010	A	0.0074	0.0009
80: post	-44.18	<0.0001	0.022	0.0019	0.018	0.027	B	0.0221	0.0017
100: pre	-37.14	<0.0001	0.006	0.0008	0.004	0.008	A	0.0056	0.0010
100: post	-45.69	<0.0001	0.015	0.0014	0.012	0.018	B	0.0147	0.0011
120: pre	-32.4	<0.0001	0.004	0.0007	0.002	0.007	A	0.0044	0.0006
120: post	-45.67	<0.0001	0.013	0.0012	0.011	0.016	B	0.0131	0.0006
Pole GSL									
20: pre	-38.45	<0.0001	0.020	0.0020	0.016	0.025	A	0.0202	0.0019
20: post	-33.21	<0.0001	0.050	0.0045	0.040	0.062	B	0.0501	0.0053
40: pre	-34.65	<0.0001	0.010	0.0014	0.008	0.014	A	0.0102	0.0002
40: post	-36.89	<0.0001	0.032	0.0030	0.026	0.039	B	0.0317	0.0012
60: pre	-33.93	<0.0001	0.010	0.0013	0.007	0.013	A	0.0096	0.0014
60: post	-37.96	<0.0001	0.026	0.0025	0.021	0.032	B	0.0255	0.0020
80: pre	-29.39	<0.0001	0.007	0.0012	0.005	0.010	A	0.0069	0.0014
80: post	-38.27	<0.0001	0.022	0.0022	0.018	0.027	B	0.0220	0.0026
100: pre	-30.13	<0.0001	0.007	0.0012	0.005	0.011	A	0.0073	0.0013
100: post	-38.08	<0.0001	0.017	0.0018	0.014	0.021	B	0.0170	0.0025
120: pre	-23.36	<0.0001	0.005	0.0011	0.003	0.009	A	0.0047	0.0008
120: post	-37.36	<0.0001	0.014	0.0016	0.011	0.018	B	0.0139	0.0015

Table A6—The analysis of variance table for pre and post quadratic mean diameter (QMD) increment response to the 1998 thinnings. These data are displayed in figure 29 in the main text in this volume, RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	5	50.50	<0.0001
Sapling/pole[b]	1	12.08	0.0013
Thinning[c]	1	435.32	<0.0001
GSL*sapling/pole*thinning[d]	16	1.03	0.4482

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Thinning = effect testing difference between tree growth before and after thinning.
[d]GSL*sapling/pole*thinning = effect testing interaction between GSL and measurement year.

Quadratic mean diameter growth (inches) thinning response. Pre-growth equals age 95 to 100 years and post-growth equals age 105 to 112 years.								True values	
GSL pre- and post-thinning	t value	Pr > |t|	LS mean	Std error	95% conf. limits lower	95% conf. limits upper	Sig. diff.	Mean	Std. error
Sapling GSL									
20: pre	-25.09	<0.0001	0.160	0.0117	0.138	0.186	A	0.160	0.001
20: post	-20.44	<0.0001	0.297	0.0176	0.260	0.339	B	0.297	0.027
40: pre	-24.94	<0.0001	0.127	0.0105	0.107	0.150	A	0.127	0.007
40: post	-22.54	<0.0001	0.247	0.0153	0.216	0.283	B	0.247	0.007
60: pre	-22.81	<0.0001	0.087	0.0093	0.069	0.109	A	0.087	0.007
60: post	-24.07	<0.0001	0.203	0.0135	0.176	0.233	B	0.203	0.023
80: pre	-22.19	<0.0001	0.080	0.0091	0.063	0.103	A	0.080	0.012
80: post	-24.13	<0.0001	0.203	0.0134	0.177	0.234	B	0.203	0.007
100: pre	-20.56	<0.0001	0.067	0.0088	0.050	0.090	A	0.067	0.013
100: post	-25.15	<0.0001	0.150	0.0113	0.128	0.175	B	0.150	0.008
120: pre	-18.26	<0.0001	0.054	0.0086	0.037	0.077	A	0.053	0.007
120: post	-25.14	<0.0001	0.142	0.0110	0.120	0.166	B	0.142	0.005
Pole GSL									
20: pre	-24.40	<0.0001	0.134	0.0110	0.113	0.159	A	0.133	0.013
20: post	-19.27	<0.0001	0.285	0.0186	0.243	0.335	B	0.286	0.022
40: pre	-22.48	<0.0001	0.080	0.0090	0.063	0.102	A	0.080	0.000
40: post	-22.10	<0.0001	0.219	0.0151	0.188	0.256	B	0.219	0.006
60: pre	-22.53	<0.0001	0.081	0.0090	0.063	0.102	A	0.080	0.012
60: post	-23.21	<0.0001	0.189	0.0136	0.162	0.221	B	0.189	0.012
80: pre	-20.14	<0.0001	0.061	0.0084	0.044	0.083	A	0.060	0.012
80: post	-23.71	<0.0001	0.172	0.0128	0.147	0.202	B	0.172	0.015
100: pre	-21.02	<0.0001	0.067	0.0086	0.050	0.089	A	0.067	0.007
100: post	-24.36	<0.0001	0.142	0.0114	0.120	0.168	B	0.142	0.013
120: pre	-23.36	<0.0001	0.005	0.0011	0.003	0.009	A	0.0047	0.0008
120: post	-37.36	<0.0001	0.014	0.0016	0.011	0.018	B	0.0139	0.0015

Table A7—The analysis of variance table for tree height. These data are displayed in figure 32 in the main text in RMRS-GTR-393.

Years 1963 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	5	4.93	0.0004
Sapling/pole[b]	1	188.14	<0.0001
Sapling/pole*year[c]	5	0.67	0.6452
GSL*year[d]	50	1.30	0.1011
Year	10	35.71	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Years 1978 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	10.34	<0.0001
Sapling/pole[b]	1	144.29	<0.0001
Sapling/pole*year[c]	6	0.64	0.7011
GSL*year[d]	30	1.38	0.1038
Year	5	18.25	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate tree height among the GSL from 1963 through 2010 and 1978 through 2010 when the unthinned plots were included. In the following table the true mean tree heights for 2010 are shown along with the standard error of the mean.

Tree height least squares means (feet)								**2010 true values**	
Sapling GSL	**t value**	**Pr > |t|**	**LS mean**	**Std error**	**95% conf. limits lower**	**upper**	**Sig. diff.**	**Mean**	**Std. error**
20 sapling	107.51	<0.0001	45.2	1.6	42.1	48.5	a	54	1.86
40 sapling	109.82	<0.0001	48.3	1.7	45.1	51.9	a	56	1.45
60 sapling	110.84	<0.0001	49.8	1.8	46.4	53.4	a	58	3.06
80 sapling	112.34	<0.0001	52.0	1.8	48.5	55.8	a	60	3.51
100 sapling	112.38	<0.0001	52.1	1.8	48.6	55.9	a	57	0.67
120 sapling	111.55	<0.0001	50.7	1.8	47.3	54.4	a	57	1.45
UnThin sap	102.71	<0.0001	39.3	1.4	36.6	42.2	b	41	1.20
Pole GSL									
20 pole	112.88	<0.0001	53.8	1.9	50.2	57.8	A	59	1.33
40 pole	114.00	<0.0001	55.5	2.0	51.7	59.5	A	60	1.33
60 pole	114.67	<0.0001	56.5	2.0	52.7	60.6	A	59	2.03
80 pole	116.95	<0.0001	60.6	2.1	56.5	65.0	A	63	0.33
100 pole	116.87	<0.0001	60.5	2.1	56.4	64.9	A	64	4.06
120 pole	117.87	<0.0001	62.5	2.2	58.2	67.0	A	64	3.48
UnThin pole	108.16	<0.0001	46.9	1.7	43.7	50.3	B	53	3.00

Table A8—The analysis of variance table for total cubic feet. These data are displayed in figure 35 in the main text in this volume, RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	5	46.62	<0.0001
Sapling/pole[b]	1	72.74	<0.0001
Sapling/pole*year[c]	5	0.81	0.5486
GSL*year[d]	50	6.46	<0.0001
Year	10	129.88	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Years 1978 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	91.30	<0.0001
Sapling/pole[b]	1	39.42	<0.0001
Sapling/pole*year[c]	6	0.99	0.435
GSL*year[d]	30	3.97	<0.0001
Year	5	36.51	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate total cubic feet among the GSL from 1963 through 2010 and 1978 through 2010 when the unthinned plots were included. In the following table the true mean total cubic feet volumes for 2010 are shown along with the standard error of the mean.

Total cubic feet per acre least squares means								2010 true values	
	t value	Pr > |t|	LS	Std	95% conf. limits		Sig.	Mean	Std.
Sapling GSL			mean	error	lower	upper	diff.		Error
20 sapling	62.88	<0.0001	349	33	290	420	e	670	25
40 sapling	72.96	<0.0001	740	67	618	886	d	1382	41
60 sapling	76.56	<0.0001	984	89	823	1177	cd	1893	117
80 sapling	78.90	<0.0001	1195	107	1000	1429	c	2372	113
100 sapling	80.31	<0.0001	1344	121	1124	1607	bc	2479	34
120 sapling	81.49	<0.0001	1485	133	1242	1776	ab	2722	336
UnThin sap	128.98	<0.0001	3031	188	2678	3432	a	3367	164
Pole GSL									
20 pole	66.50	<0.0001	497	46	413	599	D	677	29
40 pole	74.57	<0.0001	873	79	729	1046	C	1342	45
60 pole	79.49	<0.0001	1286	116	1075	1539	BC	1861	61
80 pole	82.54	<0.0001	1664	150	1391	1990	B	2466	27
100 pole	84.42	<0.0001	1941	174	1623	2320	B	2801	167
120 pole	85.63	<0.0001	2150	193	1798	2570	AB	2942	261
UnThin pole	131.87	<0.0001	3558	221	3144	4027	A	3642	30

Table A9—The analysis of variance table for merchantable (9-inch QMD, 6-inch top) total cubic feet. There was minimal merchantable volume prior to 1978, which confounded the analysis, as a result data from 1978 through 2010 was used. These data are displayed in figure 36 in the main text in this volume, RMRS-GTR-393.

Years 1978 through 2010

Effect	**Degrees of freedom**	**F Value**	**Pr > F**
GSL[a]	6	5.67	0.0001
Sapling/pole[b]	1	37.89	<0.0001
Sapling/pole*year[c]	6	6.41	<0.0001
GSL*year[d]	30	1.10	0.3381
Year	5	11.23	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate merchantable cubic feet among the GSL from 1978 through 2010 including the unthinned plots. In the following table the true mean total cubic feet volumes for 2010 are shown along with the standard error of the mean.

Merchantable (9 inch QMD, 6 inch top) cubic feet per acre least squares means								**2010 true Values**	
	t value	**Pr > |t|**	**LS**	**Std**	**95% conf. limits**		**Sig.**	**Mean**	**Std.**
Sapling GSL			**mean**	**error**	**lower**	**upper**	**diff.**		**error**
20 sapling	67.52	<0.0001	375.6	86.2	238.9	590.6	c	588	30
40 sapling	97.49	<0.0001	717.4	126.2	505.8	1017.5	b	1188	39
60 sapling	107.57	<0.0001	860.7	144.0	616.5	1201.7	b	1604	126
80 sapling	113.82	<0.0001	850.4	140.4	611.6	1182.5	a	1957	142
100 sapling	116.67	<0.0001	618.5	114.2	428.5	892.8	b	1663	143
120 sapling	119.15	<0.0001	571.3	108.1	392.4	831.7	b	1541	418
UnThin sap	128.98	<0.0001	1524.2	220.8	1135.9	2045.3	a	1962	282
Pole GSL									
20 pole	74.46	<0.0001	533.3	107.0	358.5	793.3	C	609	32
40 pole	99.19	<0.0001	882.2	148.4	630.4	1234.6	B	1193	43
60 pole	110.62	<0.0001	1065.3	171.2	771.3	1471.4	B	1615	63
80 pole	118.3	<0.0001	1616.3	246.0	1188.0	2198.9	A	2134	43
100 pole	122.12	<0.0001	1712.3	270.9	1243.8	2357.5	A	2311	264
120 pole	124.52	<0.0001	1719.5	270.8	1250.7	2364.1	A	2345	284
UnThin pole	131.87	<0.0001	1239.2	184.6	917.3	1674.0	B	1444	375

Table A10—The analysis of variance table for Scribner board foot volume. There was minimal board foot volume prior to 1978, which confounded the analysis, as a result data from 1978 through 2010 was used. These data are displayed in figure 37 in the main text in this volume, RMRS-GTR-393.

Years 1978 through 2010

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	3.73	0.0057
Sapling/pole[b]	1	46.74	<0.0001
Sapling/pole*year[c]	6	7.05	<0.0001
GSL*year[d]	30	1.83	0.0104
Year	5	13.4	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and measurement year.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate board feet volume among the GSL from 1978 through 2010 including the unthinned plots. In the following table the true mean total board feet volumes for 2010 are shown along with the standard error of the mean.

Board feet per acre least squares means								2010 true values	
	t value	Pr > |t|	LS	Std	95% conf. limits		Sig.	Mean	Std.
Sapling GSL			mean	error	lower	upper	diff.		error
20 sapling	33.89	<0.0001	1788.6	395.3	1149.8	2782.4	c	2840	92
40 sapling	38.33	<0.0001	3094.6	648.9	2025.2	4728.7	b	5787	81
60 sapling	39.15	<0.0001	3487.6	726.6	2286.8	5319.2	b	7600	794
80 sapling	39.01	<0.0001	3541.3	741.8	2317.1	5412.3	a	9107	819
100 sapling	35.72	<0.0001	2488.7	544.9	1602.7	3864.5	b	7733	608
120 sapling	34.65	<0.0001	2228.9	495.9	1425.9	3484.3	b	7307	1949
UnThin sap	44.51	<0.0001	7996.6	1614.6	5295.2	12076.0	a	10053	1375
Pole GSL									
20 pole	35.14	<0.0001	2420.0	536.6	1549.9	3778.4	C	3147	201
40 pole	39.17	<0.0001	4183.3	890.7	2719.4	6435.2	B	6000	243
60 pole	41.17	<0.0001	5736.5	1206.0	3743.7	8790.2	B	7833	403
80 pole	42.30	<0.0001	7162.2	1503.1	4676.1	10970.0	A	10253	320
100 pole	41.33	<0.0001	7526.0	1625.6	4858.2	11659.0	A	11233	1632
120 pole	41.63	<0.0001	7848.0	1690.6	5069.5	12149.0	A	11333	1478
UnThin pole	42.50	<0.0001	5529.0	1121.2	3657.7	8357.7	B	7406	1881

Table A11—The analysis of variance table for trees removed from the GSL plots and those that died in the unthinned plots from 1963 through 2010. High variability of trees removed among the GSL occurred from 1963 through 2010 that confounded the analysis. As a result the pole and sapling plots were analyzed separately. These data are displayed in figure 38 in the main text in this volume, RMRS-GTR-393. Also the true trees removed and lost through 2010 are shown along with the standard error of the means.

Sapling plots

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	306.81	<0.0001

[a]GSL = Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).

Trees per acre removed from the GSL plots and the number of trees per acre that died in the unthinned plots								2010 true values	
	t value	Pr > |t|	LS	Std	95% conf. limits		Sig.	Mean	Std.
Sapling GSL			mean	error	lower	upper	diff.		error
20 sapling	79.85	<0.0001	86.7	4.8	76.9	97.7	c	86.7	2.2
40 sapling	28.57	<0.0001	154.7	27.3	105.9	225.8	b	154.7	4.4
60 sapling	30.44	<0.0001	172.0	29.1	119.7	247.2	ab	172.0	21.7
80 sapling	44.85	<0.0001	209.3	24.9	162.1	270.3	ab	209.3	16.0
100 sapling	56.41	<0.0001	244.0	23.8	198.0	300.7	a	244.0	16.4
120 sapling	63.77	<0.0001	340.0	31.1	279.5	413.6	a	340.0	34.9
UnThin sap	55.61	<0.0001	396.0	42.6	314.4	498.8	a	348.3	67.3

Pole plots

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	104.43	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).

Trees per acre removed from the GSL plots and the number of trees per acre that died in the unthinned plots								2010 true values	
	t value	Pr > |t|	LS	Std	95% conf. limits		Sig.	Mean	Std.
Pole GSL			mean	error	lower	upper	diff.		error
20 pole	29.00	<0.0001	44.0	5.7	33.3	58.2	D	44.0	5.7
40 pole	230.67	<0.0001	86.0	1.7	82.5	89.6	C	86.0	1.6
60 pole	75.86	<0.0001	126.7	8.1	110.5	145.3	B	126.7	8.0
80 pole	65.29	<0.0001	140.0	10.6	119.0	164.7	B	140.0	10.5
100 pole	83.92	<0.0001	168.7	10.3	148.0	192.3	AB	168.7	10.2
120 pole	138.19	<0.0001	191.3	7.3	176.4	207.6	A	191.3	7.9
UnThin pole	55.38	<0.0001	244.3	24.3	197.5	302.3	A	244.3	23.6

Table A12—The analysis of variance table for cubic volume removed from the GSL plots and the cubic volume lost in the unthinned plots from 1963 through 2010. High variability of volume removed among the GSL occurred from 1963 through 2010 that confounded the analysis. As a result the pole and sapling plots were analyzed separately. These data are displayed in figure 39 in the main text in this volume, RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	2.36	0.0873

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).

In the following two tables least square means were used to separate cubic foot volume removed from the GSL and lost in the unthinned plots from 1963 through 2010. Also the true cubic feet means removed and lost through 2010 are shown along with the standard error of the means.

Sapling plots

Cubic volume removed and lost (cubic feet per acre)								2010 true values	
Sapling GSL	t value	Pr > |t|	LS mean	Std error	95% conf. limits lower	95% conf. limits upper	Sig. diff.	Mean	Std. error
20 sapling	90.82	<0.0001	453.67	30.56	392.64	524.18	a	453.7	30.6
40 sapling	72.09	<0.0001	573.33	50.51	474.61	692.59	a	573.3	50.5
60 sapling	43.74	<0.0001	621.33	91.37	453.26	851.73	a	621.3	91.4
80 sapling	40.61	<0.0001	602.67	95.00	429.77	845.11	a	602.7	95.0
100 sapling	16.06	<0.0001	385.67	143.00	174.11	854.27	a	385.7	143.0
120 sapling	273.3	<0.0001	555.00	12.83	528.15	583.22	a	555.0	12.8
UnThin sap	30.92	<0.0001	834.33	181.53	523.21	1330.46	a	834.3	181.5

Pole plots

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	6.27	0.0023

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).

Cubic volume removed and lost (cubic feet per acre)								2010 true values	
Pole GSL	t value	Pr > |t|	LS mean	Std error	95% conf. limits lower	95% conf. limits upper	Sig. diff.	Mean	Std. error
20 pole	94.03	<0.0001	535.67	35.80	464.14	618.22	B	535.7	35.8
40 pole	169.19	<0.0001	645.33	24.68	594.52	700.49	A	645.3	24.7
60 pole	61.03	<0.0001	875.67	97.21	690.13	1111.08	A	875.7	97.2
80 pole	56.99	<0.0001	894.67	106.69	692.76	1155.41	A	894.7	106.7
100 pole	27.04	<0.0001	938.00	237.43	545.04	1614.27	A	938.0	237.4
120 pole	31.78	<0.0001	1284.33	289.26	792.31	2081.92	A	1284.3	289.3
UnThin pole	19.67	<0.0001	1363.33	500.18	620.68	2994.6	A	1363.3	500.2

Table A13—The analysis of variance table for cubic volume yield (i.e. standing 2010 volume plus the volume removed in the thinnings). Least square means were used to separate cubic foot yield in the unthinned plots from 1963 through 2010. Standing 2010 volume was used for the unthinned plots. In the following table the true mean total board feet yield for 2010 are shown along with the standard error of the mean. These data are displayed in figure 40 in the main text, this volume, RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	198.31	<.0001
Sapling/pole[b]	1	18.57	0.0002
Sapling/pole*GSL[c]	6	1.27	0.3023

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and GSL.

Cubic foot yield (harvest plus standing volume 2010) and standing volume in the unthinned plots least squares means (cubic feet per acre)								**2010 true values**	
	t value	**Pr > |t|**	**LS**	**Std**	**95% conf. limits**		**Sig.**	**Mean**	**Std.**
Sapling GSL			**mean**	**error**	**lower**	**upper**	**diff.**		**error**
20 sapling	159.69	<0.0001	1124.0	49.4	1027.2	1230.0	c	588	30
40 sapling	212.22	<0.0001	1955.0	69.8	1817.1	2103.4	b	1188	39
60 sapling	117.61	<0.0001	2514.3	167.4	2193.8	2881.7	ab	1604	126
80 sapling	127.15	<0.0001	2975.0	187.1	2615.4	3384.1	a	1957	142
100 sapling	149.99	<0.0001	2865.0	152.1	2569.9	3194.0	a	1663	143
120 sapling	101.21	<0.0001	3276.7	262.1	2781.5	3859.9	a	1541	418
UnThin sap	204.32	<0.0001	3366.7	133.8	3103.4	3652.3	a	1962	282
Pole GSL									
20 pole	186.33	<0.0001	1212.3	46.2	1121.3	1310.8	D	609	32
40 pole	253.98	<0.0001	1987.7	59.4	1869.6	2113.2	C	1193	43
60 pole	152.88	<0.0001	2737.0	141.7	2461.6	3043.2	B	1615	63
80 pole	220.61	<0.0001	3361.0	123.7	3116.9	3624.2	AB	2134	43
100 pole	83.03	<0.0001	3739.0	370.5	3052.2	4580.4	AB	2311	264
120 pole	120.13	<0.0001	4226.3	293.7	3665.5	4873.0	A	2345	284
UnThin pole	1219.03	<0.0001	3642.0	24.5	3592.2	3692.5	AB	1444	375

Table A14—The analysis of variance table for merchantable cubic (9-inch QMD, 6-inch top) volume yield (i.e. standing 2010 volume plus the volume removed in the thinnings). The 2010 standing volume of the unthinned plots was used in this analysis. These data are displayed in figure 41 in the main text in this volume, RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	18.61	<0.0001
Sapling/pole[b]	1	8.89	0.0059
Sapling/pole*GSL[c]	6	3.82	0.0066

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and GSL.

Least square means were used to separate merchantable cubic foot yield (harvest plus standing volume 2010) and standing volume in the unthinned plots from 1963 through 2010. In the following table the true merchantable cubic foot yield for 2010 are shown along with the standard error of the mean.

Merchantable cubic foot yield (harvest plus standing volume 2010) and standing volume in the unthinned plots least squares means (cubic feet per acre)								**2010 true values**	
Sapling GSL	**t value**	**Pr > |t|**	**LS mean**	**Std error**	**95% conf. limits lower**	**upper**	**Sig. diff.**	**Mean**	**Std. error**
20 sapling	115.60	<0.0001	934.0	55.3	827.4	1054.3	b	934.0	47.2
40 sapling	190.76	<0.0001	1595.7	61.7	1474.2	1727.2	a	1595.7	230.3
60 sapling	66.71	<0.0001	1767.7	198.2	1405.0	2223.9	a	1767.7	93.0
80 sapling	107.77	<0.0001	2019.7	142.6	1747.7	2334.0	a	2019.7	32.4
100 sapling	95.73	<0.0001	1717.7	133.7	1464.6	2014.5	a	1717.7	295.2
120 sapling	40.48	<0.0001	1629.7	297.7	1120.9	2369.3	a	1629.7	318.3
UnThin sap	316.63	<0.0001	2364.7	58.0	2248.8	2486.5	a	1961.7	60.7
Pole GSL									
20 pole	45.31	<0.0001	941.7	142.3	691.0	1283.3	B	941.7	48.0
40 pole	233.14	<0.0001	1708.7	54.6	1600.5	1824.2	B	941.7	88.5
60 pole	31.73	<0.0001	3119.7	790.9	1856.0	5243.8	A	3119.7	36.0
80 pole	124.23	<0.0001	2593.7	164.1	2278.4	2952.6	A	2593.7	267.6
100 pole	50.12	<0.0001	2766.7	437.5	2001.2	3825.0	A	2766.7	238.9
120 pole	79.48	<0.0001	2873.0	287.9	2339.9	3527.5	A	2873.0	555.8
UnThin pole	34.26	<0.0001	1443.7	306.5	934.5	2230.3	B	1444.0	27.7

Table A15—The analysis of variance table for Scribner board foot volume yield (i.e. standing 2010 volume plus the volume removed in the thinnings). The 2010 standing volume of the unthinned plots was used in this analysis. These data are displayed in figure 42 in the main text in this volume, RMRS-GTR-393.

Effect	**Degrees of freedom**	**F Value**	**Pr > F**
GSL[a]	6	16.68	<.0001
Sapling/pole[b]	1	11.33	0.0022
Sapling/pole*GSL[c]	6	2.81	0.0287

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*year = effect testing interaction between plot type and GSL.

Least square means were used to separate Scribner board foot volume yield among the GSL from 1963 through 2010. Standing 2010 volume as used for the unthinned plots. In the following table the true mean total board feet yield for 2010 are shown along with the standard error of the mean.

Scribner board foot yield (harvest plus standing volume 2010) and standing volume in the unthinned plots least squares means (cubic feet per acre)								**2010 true values**	
Sapling GSL	**t value**	**Pr > |t|**	**LS mean**	**Std error**	**95% conf. limits lower**	**upper**	**Sig. diff.**	**Mean**	**Std. error**
20 sapling	67.54	<0.0001	3410	410.7	2664	3821	b	3410	459
40 sapling	295.02	<0.0001	7253	218.6	6819	7472	a	7253	768
60 sapling	71.38	<0.0001	8427	1067.1	6501	9494	a	8427	616
80 sapling	108.96	<0.0001	9387	788.0	7904	10175	a	9387	272
100 sapling	121.69	<0.0001	8013	591.9	6888	8605	a	8013	623
120 sapling	50.00	<0.0001	7729	1383.8	5356	9112	a	7733	938
UnThin sap	82.53	<0.0001	10053	1122.6	7998	11176	a	10053	204
Pole GSL									
20 pole	55.20	<0.0001	4773	732.5	3486	5506	C	4773	743
40 pole	113.46	<0.0001	7407	581.7	6306	7988	B	7407	958
60 pole	96.99	<0.0001	9487	895.7	7819	10382	B	9487	1047
80 pole	140.80	<0.0001	12660	849.4	11034	13509	A	12660	1361
100 pole	52.74	<0.0001	13498	2433.9	9329	15932	A	13507	1316
120 pole	85.65	<0.0001	14018	1562.8	11156	15581	A	14018	2115
UnThin pole	42.64	<0.0001	7358	1536.4	4798	8895	BC	7406	249

Table A16—The analysis of variance table for mountain pine beetle (MPB) impacts to basal area among the GSL and unthinned plots from 2010 through 2014. These data are displayed in figure 47 in the main text in this volume, RMRS-GTR-393, p. 48.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	41.36	<.0001
Sapling/pole[b]	1	0.09	0.7653
Sapling/pole*GSL[c]	6	1.20	0.3117
GSL*year[d]	18	4.08	<0.0001
Year	3	68.46	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*GSL = effect testing interaction between plot type and GSL.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate basal area per acre lost to mountain pine beetles (MPB) among the GSL from 2010 through 2014 including the unthinned plots. In the following table the true basal area means lost to MPBs are shown along with the standard error of the means.

Basal area per acre least squares means (square feet per acre)								**2010 true values**	
Sapling GSL/year	**t value**	**Pr > |t|**	**LS mean**	**Std error**	**95% conf. limits lower**	**upper**	**Sig. diff.**	**Mean**	**Std. error**
20/2010	18.44	<0.0001	27.5	4.9	19.3	39.3	a	29.0	0.6
20/2014	12.90	<0.0001	21.0	5.0	13.1	33.5	a	21.7	0.9
40/2010	45.54	<0.0001	56.0	4.9	47.0	66.7	a	59.0	1.0
40/2014	22.95	<0.0001	32.7	5.0	24.2	44.2	b	33.3	12.5
60/2010	69.41	<0.0001	78.8	5.0	69.6	89.3	a	81.7	1.5
60/2014	27.92	<0.0001	38.2	5.0	29.5	49.5	b	27.7	1.8
80/2010	92.75	<0.0001	100.1	5.0	90.7	110.5	a	103.3	1.5
80//2014	24.77	<0.0001	34.7	5.0	26.2	46.1	b	11.3	8.3
100/2010	109.72	<0.0001	115.2	5.0	105.7	125.5	a	117.7	1.2
100/2014	15.07	<0.0001	23.6	5.0	15.6	35.8	b	17.0	8.6
120/2010	123.12	<0.0001	126.9	5.0	117.4	137.1	a	131.3	10.4
120/2014	23.01	<0.0001	32.8	5.0	24.3	44.2	b	36.3	19.0
UnThin/2010	157.05	<0.0001	156.0	5.0	146.4	166.2	a	151.7	2.2
UnThin/2014	16.21	<0.0001	24.9	4.9	16.8	36.9	b	18.0	6.6
Pole GSL/year									
20/2010	16.57	<0.0001	24.7	8.6	17.3	35.2	A	26.0	1.0
20/2014	11.78	<0.0001	19.7	1.9	12.3	31.4	A	20.3	0.3
40/2010	43.48	<0.0001	50.3	5.7	42.2	59.9	A	53.0	1.2
40/2014	22.15	<0.0001	31.4	2.4	23.2	42.4	B	32.0	6.1
60/2010	68.92	<0.0001	73.4	0.0	64.8	83.1	A	76.0	0.0
60/2014	27.78	<0.0001	67.2	16.3	51.9	87.0	B	48.7	5.8
80/2010	94.54	<0.0001	94.0	2.0	85.2	103.7	A	97.0	0.6
80//2014	25.01	<0.0001	175.8	4.4	132.4	233.4	B	57.3	7.3
100/2010	116.85	<0.0001	110.3	18.1	101.2	120.1	A	112.7	4.4
100/2014	17.10	<0.0001	41.7	11.4	27.5	63.2	B	30.0	19.9
120/2010	134.65	<0.0001	118.2	5.2	109.3	127.7	A	122.3	10.8
120/2014	26.68	<0.0001	25.9	4.3	19.2	34.9	B	28.7	16.3
UnThin/2010	192.86	<0.0001	165.6	24.3	155.4	176.4	A	161.0	10.6
UnThin/2014	24.25	<0.0001	43.4	2.1	29.3	64.3	B	31.3	2.7

Table A17—The analysis of variance table for mountain pine beetle (MPB) impacts to trees per acre among the GSL and unthinned plots from 2010 through 2014. These data are displayed in figure 48 in the main text in this volume, RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	37.12	<0.0001
Sapling/pole[b]	1	32.03	<0.0001
Sapling/pole*GSL[c]	6	1.27	0.2756
GSL*year[d]	18	2.94	0.0002
Year	3	69.24	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*GSL = effect testing interaction between plot type and GSL.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate basal area per acre lost to mountain pine beetles (MPB) among the GSL from 2010 through 2014 including the unthinned plots. In the following table the true basal area means lost to MPBs are shown along with the standard error of the means.

Sapling trees per acre least squares means.								2010 true values	
Sapling GSL/year	t value	Pr > |t|	LS mean	Std error	95% conf. limits lower	95% conf. limits upper	Sig. diff.	Mean	Std. error
20/2010	27.92	<0.0001	19.0	2.0	15.4	23.4	a	24.0	2.3
20/2014	8.09	<0.0001	14.3	4.7	7.5	27.4	a	17.3	1.3
40/2010	37.54	<0.0001	52.5	5.5	42.6	64.7	a	60.0	0.0
40/2014	10.05	<0.0001	27.3	9.0	14.2	52.2	a	33.3	13.5
60/2010	42.64	<0.0001	90.0	9.5	73.0	110.8	a	106.7	9.3
60/2014	11.26	<0.0001	40.5	13.3	21.1	77.6	b	36.0	6.1
80/2010	46.12	<0.0001	129.8	13.7	105.3	159.9	a	153.3	14.1
80/2014	9.77	<0.0001	24.9	8.2	13.0	47.6	b	20.0	16.0
100/2010	49.43	<0.0001	184.0	19.4	149.3	226.7	a	224.0	15.1
100/2014	9.57	<0.0001	23.2	7.6	12.1	44.5	b	34.7	12.7
120/2010	51.43	<0.0001	227.4	24.0	184.6	280.2	a	277.3	11.4
120/2014	10.86	<0.0001	35.6	11.7	18.6	68.2	b	86.7	42.4
UnThin/2010	58.4	<0.0001	474.5	50.1	385.1	584.6	a	462.7	38.9
UnThin/2014	14.47	<0.0001	116.5	38.3	60.8	223.2	b	121.3	49.0
Pole GSL/year									
20/2010	17.84	<0.0001	12.1	1.2	9.8	15.0	A	15.3	1.3
20/2014	15.23	<0.0001	9.9	4.2	5.2	19.0	A	12.0	1.2
40/2010	22.66	<0.0001	40.3	10.1	32.7	49.6	A	46.0	2.0
40/2014	21.01	<0.0001	22.4	3.9	11.7	42.8	A	27.3	5.8
60/2010	25.86	<0.0001	64.7	3.8	52.5	79.6	A	76.7	3.7
60/2014	23.6	<0.0001	54.0	15.3	28.1	103.5	A	48.0	7.0
80/2010	27.24	<0.0001	94.3	8.1	76.5	116.1	A	111.3	8.4
80/2014	24.02	<0.0001	82.2	2.1	42.9	157.1	B	66.0	4.2
100/2010	28.15	<0.0001	129.2	38.1	104.9	159.2	A	157.3	29.7
100/2014	26.02	<0.0001	33.0	22.7	17.2	63.3	B	49.3	37.8
120/2010	29.91	<0.0001	156.9	64.4	127.4	193.3	A	191.3	30.6
120/2014	27.49	<0.0001	17.2	5.7	9.0	33.0	B	42.0	20.8
UnThin/2010	33.54	<0.0001	518.2	106.5	420.6	638.5	A	505.3	82.8
UnThin/2014	33.68	<0.0001	136.4	22.3	71.2	261.3	B	142.0	28.6

Table A18—The analysis of variance table for mountain pine beetle (MPB) impacts to cubic feet volume among the GSL and unthinned plots from 2010 through 2014. These data are displayed in figure 49 in the main text in this volume, RMRS-GTR-393

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	30.71	<0.0001
Sapling/pole[b]	1	2.74	0.1006
Sapling/pole*GSL[c]	6	0.25	0.9583
GSL*year[d]	18	3.96	<0.0001
Year	3	83.1	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*GSL = effect testing interaction between plot type and GSL.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate cubic feet per acre lost to mountain pine beetles (MPB) among the GSL from 2010 through 2014 including the unthinned plots. In the following table the true cubic feet per acre means lost to MPBs are shown along with the standard error of the means.

Cubic feet per acre least squares means								2010 true values	
Sapling GSL/year	t value	Pr > |t|	LS mean	Std error	95% conf. limits lower	upper	Sig. diff.	Mean	Std. error
20/2010	46.68	<0.0001	673.0	93.9	510.8	886.9	a	670.3	25.4
20/2014	97.05	<0.0001	518.6	104.9	347.6	773.6	a	507.0	23.7
40/2010	129.42	<0.0001	1359.8	101.1	1173.8	1575.2	a	1381.7	41.3
40/2014	156.66	<0.0001	810.6	121.6	601.0	1093.2	b	776.3	265.6
60/2010	166.87	<0.0001	1874.1	109.1	1670.2	2102.9	a	1893.0	116.8
60/2014	175.34	<0.0001	933.4	130.0	705.7	1234.4	b	642.0	33.5
80/2010	198.32	<0.0001	2399.4	119.2	2173.6	2648.6	a	2372.3	113.3
80/2014	30.92	<0.0001	909.4	128.0	685.2	1206.8	b	231.0	156.1
100/2010	44.66	<0.0001	2628.5	124.0	2392.2	2888.1	a	2479.3	34.0
100/2014	49.08	<0.0001	573.6	106.2	397.8	827.2	b	348.0	188.1
120/2010	48.39	<0.0001	2829.2	128.2	2583.7	3098.0	a	2721.7	336.1
120/2014	34.32	<0.0001	766.2	117.7	563.9	1041.0	b	703.3	380.1
UnThin/2010	43.25	<0.0001	3502.1	144.1	3222.4	3806.0	a	3366.7	163.9
UnThin/2014	25.82	<0.0001	427.3	100.2	268.7	679.6	b	266.7	74.3
Pole GSL/year									
20/2010	47.6	<0.0001	679.4	108.5	515.6	895.3	A	676.7	29.4
20/2014	50.1	<0.0001	542.1	75.6	363.4	808.7	A	530.0	17.1
40/2010	82.8	<0.0001	1321.1	109.6	1140.4	1530.3	A	1342.3	44.7
40/2014	83.1	<0.0001	847.1	58.7	628.1	1142.5	B	811.3	128.3
60/2010	97.3	<0.0001	1842.7	57.0	1642.3	2067.7	A	1861.3	61.1
60/2014	99.9	<0.0001	1742.2	484.1	1317.3	2304.0	B	1198.3	124.7
80/2010	106.0	<0.0001	2494.5	28.8	2259.7	2753.6	A	2466.3	27.4
80/2014	110.1	<0.0001	5750.1	169.8	4332.8	7630.9	B	1460.7	207.1
100/2010	99.0	<0.0001	2969.5	607.3	2702.6	3262.8	A	2801.0	166.6
100/2014	102.9	<0.0001	1121.4	230.8	777.7	1617.1	B	680.3	409.0
120/2010	110.3	<0.0001	3058.2	99.6	2792.9	3348.8	A	2942.0	261.2
120/2014	112.7	<0.0001	794.5	135.8	584.8	1079.5	B	729.3	438.5
UnThin/2010	96.3	<0.0001	3788.5	26.4	3485.9	4117.3	A	3642.0	30.0

Table A19—The analysis of variance table for mountain pine beetle (MPB) impacts to merchantable cubic feet volume among the GSL and unthinned plots from 2010 through 2014. These data are displayed in figure 50 in the main text in this volume, RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	3.50	0.0033
Sapling/pole[b]	1	0.62	0.4345
Sapling/pole*GSL[c]	6	2.60	0.0217
GSL*year[d]	18	6.79	<0.0001
Year	3	100.75	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*GSL = effect testing interaction between plot type and GSL.
[d]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate merchantable cubic feet per acre lost to mountain pine beetles (MPB) among the GSL from 2010 through 2014 including the unthinned plots. In the following table the true cubic feet per acre means lost to MPBs are shown along with the standard error of the means.

Merchantable cubic feet per acre least squares means.								2010 true values	
Sapling GSL/year	t value	Pr > |t|	LS mean	Std error	95% conf. limits lower	upper	Sig. diff.	Mean	Std. error
20/2010	52.18	<0.0001	594.6	72.8	466.5	757.9	a	588.0	29.6
20/2014	16.05	<0.0001	456.4	174.1	214.3	972.1	a	1188.3	38.7
40/2010	57.83	<0.0001	1183.3	144.8	928.5	1508.1	a	1604.0	125.5
40/2014	16.95	<0.0001	640.6	244.2	301.0	1363.7	b	1956.7	141.7
60/2010	60.36	<0.0001	1608.9	196.8	1262.5	2050.3	a	1663.3	142.9
60/2014	17.40	<0.0001	756.1	288.0	355.4	1608.6	b	1540.7	418.5
80/2010	62.30	<0.0001	2061.0	252.5	1616.8	2627.4	a	1961.7	281.6
80/2014	16.11	<0.0001	466.5	177.9	219.0	993.4	b	447.0	26.3
100/2010	61.90	<0.0001	1963.1	240.5	1539.9	2502.6	a	672.0	223.3
100/2014	13.98	<0.0001	207.3	79.1	97.3	441.6	b	540.7	35.5
120/2010	61.15	<0.0001	1769.6	216.4	1388.7	2254.9	a	169.7	105.5
120/2014	14.20	<0.0001	221.9	84.4	104.4	471.7	b	217.0	150.8
UnThin/2010	60.37	<0.0001	1608.7	196.7	1262.4	2049.9	a	293.7	219.5
UnThin/2014	9.93	<0.0001	43.9	16.7	20.6	93.4	b	69.3	45.5
Pole GSL/year									
20/2010	9.9	<0.0001	615.5	79.3	482.9	784.6	A	608.7	32.2
20/2014	38.4	<0.0001	183.1	58.9	85.9	389.9	A	476.7	13.1
40/2010	19.2	<0.0001	879.9	49.9	690.4	1121.3	A	1192.7	43.3
40/2014	61.6	<0.0001	237.0	193.0	111.4	504.6	A	724.0	112.0
60/2010	24.2	<0.0001	1561.8	87.3	1225.6	1990.3	A	1614.7	63.4
60/2014	84.8	<0.0001	511.2	73.9	240.3	1087.6	B	1041.7	107.3
80/2010	21.8	<0.0001	2242.4	38.3	1759.1	2858.7	A	2134.3	42.7
80/2014	103.2	<0.0001	1322.5	1292.2	621.0	2816.5	B	1267.3	190.8
100/2010	13.9	<0.0001	6751.1	284.8	5295.8	8606.4	A	2311.0	264.5
100/2014	117.8	<0.0001	197.7	655.7	92.8	421.2	B	515.7	294.5
120/2010	21.6	<0.0001	24461.0	583.2	19195.8	31170.0	A	2345.3	284.2
120/2014	154.9	<0.0001	605.1	217.4	284.7	1286.2	B	591.7	388.3
UnThin/2010	17.1	<0.0001	7908.3	336.6	6206.2	10077.4	A	1443.7	375.4
UnThin/2014	14.5	<0.0001	50.9	21.0	23.9	108.3	B	80.3	57.2

Table A20—The analysis of variance table for mountain pine beetle (MPB) impacts to Scribner board foot volume among the GSL and unthinned plots from 2010 through 2014. These data are displayed in figure 51 in the main text in this volume, RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	7.10	0.0001
Sapling/pole[b]	1	0.62	0.4345
Sapling/pole*GSL[c]	6	3.98	0.0367
GSL*year[d]	18	1.42	0.2034
Year	3	25.36	<0.0001

[a]GSL=Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole=effect testing difference between sapling and pole plots.
[c]Sapling/pole*GSL=effect testing interaction between plot type and GSL.
[d]GSL*year=effect testing interaction between GSL and measurement year.

Least square means were used to separate board feet per acre lost to mountain pine beetles (MPB) among the GSL from 2010 through 2014 including the unthinned plots. In the following table the true board feet per acre means lost to MPBs are shown along with the standard error of the means

Board feet per acre least squares means.								2010 true values	
Sapling GSL/year	t value	Pr > |t|	LS mean	Std error	95% conf. limits lower	upper	Sig. diff.	Mean	Std. error
20/2010	46.14	<0.0001	2840.0	489.5	1968.6	4097.1	a	2840.0	92.4
20/2014	21.2	<0.0001	2186.5	793.2	1037.2	4609.4	a	2186.7	66.7
40/2010	71.08	<0.0001	5780.0	704.4	4516.0	7397.9	a	5786.7	81.1
40/2014	23.94	<0.0001	3300.3	1117.0	1571.7	6929.9	b	3373.3	1134.3
60/2010	78.57	<0.0001	7588.7	862.9	5984.6	9622.7	a	7600.0	794.3
60/2014	22.37	<0.0001	2566.0	900.3	1225.1	5374.9	b	2586.7	265.7
80/2010	82.96	<0.0001	9095.1	999.4	7189.2	11506.0	a	9106.7	818.6
80/2014	10.78	<0.0001	739.1	452.7	190.3	2871.1	b	760.0	461.3
100/2010	79.37	<0.0001	7716.4	870.2	6093.7	9771.3	a	7733.3	607.7
100/2014	13.33	<0.0001	1010.8	524.5	348.9	2928.2	b	1000.0	688.6
120/2010	77.38	<0.0001	7249.6	832.8	5691.1	9234.8	a	7306.7	1948.9
120/2014	15.95	<0.0001	1381.7	626.6	534.4	3572.2	b	1440.0	1082.5
UnThin/2010	84.92	<0.0001	9999.4	1084.5	7900.1	12656.0	a	10053.3	1374.9
UnThin/2014	5.85	<0.0001	354.8	356.2	15.6	8078.0	b	360.0	249.8
Pole GSL/year									
20/2010	53.68	<0.0001	3150.7	472.8	2283.7	4346.8	A	3146.7	200.8
20/2014	23.40	<0.0001	2470.4	824.7	1259.1	4846.9	A	2473.3	96.8
40/2010	76.56	<0.0001	5999.8	681.8	4778.2	7533.7	A	6000.0	243.3
40/2014	25.82	<0.0001	3595.4	1140.0	1871.0	6908.8	B	3626.7	538.2
60/2010	83.96	<0.0001	7831.9	836.4	6311.8	9718.2	A	7833.3	403.4
60/2014	27.63	<0.0001	5029.3	1551.4	2636.3	9594.6	B	5060.0	515.9
80/2010	90.10	<0.0001	10243.0	1049.9	8301.3	12640.0	A	10253.3	320.5
80/2014	28.40	<0.0001	5974.3	1828.9	3136.0	11381.0	B	6093.3	952.8
100/2010	91.60	<0.0001	11164.0	1136.0	9053.1	13768.0	A	11233.3	1631.6
100/2014	22.80	<0.0001	2588.6	892.4	1287.6	5204.0	B	2466.7	1361.8
120/2010	91.60	<0.0001	11145.0	1133.8	9038.6	13742.0	A	11333.3	1477.9
120/2014	22.69	<0.0001	2537.4	876.8	1264.7	5090.9	B	2860.0	1841.8
UnThin/2010	80.71	<0.0001	7221.9	795.0	5787.9	9011.1	A	7405.7	1881.4
UnThin/2014	8.29	<0.0001	431.4	315.8	85.3	2182.5	B	450.7	305.0

Table A21—The analysis of variance table for periodic annual basal area increment (PAI-BA) among the GSL and unthinned plots from 1963 through 2010. These data are displayed in figure 53 in the main text in RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	70.34	<0.0001
Sapling/pole[b]	1	2.72	0.1101
Sapling/pole*GSL[c]	6	1.35	0.2696

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*GSL = effect testing interaction between plot type and GSL.

Least square means were used to separate PAI-BA (square feet per acre per year) among the GSL and unthinned plots from 1963 through 2010. In the following table the true PAI-BA means are shown along with the standard error of the means.

PIA-BA (square feet per acre per year) for the GSL from 1963 through 2010 and for the unthinned plots from 1978 through 2010								True values sq ft/ac/yr			
	t value	Pr > |t|	LS	Std	95% limits		Sig.	Saplings		Poles	
GSL			mean	error	lower	upper	diff.	mean	error	Mean	error
20	79.12	<0.0001	1.93	0.02	1.90	1.97	B	1.09	0.34	0.79	0.93
40	19.71	<0.0001	2.40	0.11	2.19	2.62	B	1.64	0.92	1.17	0.21
60	47.09	<0.0001	2.88	0.06	2.75	3.01	A	2.20	2.02	1.58	1.59
80	16.92	<0.0001	3.13	0.21	2.72	3.59	A	2.45	2.46	1.83	1.94
100	31.33	<0.0001	2.80	0.09	2.62	3.00	AB	2.28	3.45	1.39	3.48
120	7.48	<0.0001	2.84	0.40	2.13	3.77	AB	1.09	5.78	1.48	1.43
UnThin	0.86	<0.0001	1.24	0.31	0.74	2.08	B	0.04	6.75	0.48	14.72

Table A22—The analysis of variance table for periodic annual cubic feet increment (PAI-CF) (cubic feet per acre per year) among the GSL from 1963 through 2010 and unthinned plots from 1978 through 2010. These data are displayed in figure 554 in the main text in this volume RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	6	57.51	<.0001
Sapling/pole[b]	1	0.65	0.4268
Sapling/pole*GSL[c]	6	0.45	0.8385

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120, unthinned).
[b]Sapling/pole = effect testing difference between sapling and pole plots.
[c]Sapling/pole*GSL = effect testing interaction between plot type and GSL.

Least square means were used to separate PAI-CF (cubic feet per acre per year) means among the GSL from 1963 through 2010 and unthinned plots from 1978 through 2010. In the following table the true PAI-CFI means are shown along with the standard error of the means.

PAI-CF (cubic feet per acre per year) for the GSL from 1963 through 2010 and for the unthinned plots from 1978 through 2010								True values cf/ac/yr			
	t value	Pr > |t|	LS	Std	95% limits		Sig.	Saplings		Poles	
GSL			mean	error	lower	upper	diff.	mean	error	Mean	error
20	91.75	<0.0001	24.04	0.83	22.39	25.81	B	25.05	1.48	23.07	1.41
40	41.22	<0.0001	37.30	3.28	31.16	44.65	A	38.24	8.00	36.38	1.81
60	76.62	<0.0001	51.47	2.65	46.32	57.19	A	54.35	4.24	48.74	4.82
80	73.19	<0.0001	58.77	3.27	52.44	65.87	A	61.39	3.26	56.26	7.07
100	101.09	<0.0001	52.80	2.07	48.72	57.22	A	54.39	3.15	51.26	3.93
120	31.77	<0.0001	54.49	6.86	42.11	70.51	A	60.39	1.48	49.17	13.47
UnThin	6.27	<0.0001	25.40	13.10	8.83	73.06	AB	12.16	14.82	53.09	17.62

Table A23—The analysis of variance table for periodic mean annual cubic volume (PAI-C-2003 periods were not used as major thinnings took place. Also the 2007–2010 periods were omitted for the sapling GSL 120 and pole GSL 100 and 120 plots as MPBs were impacting those plots. These data are displayed in figure 55 in the main text in this volume RMRS-GTR-393.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	5	113.21	<.0001
GSL*year[b]	30	72.3	<.0001
Year	6	3.35	<.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120).
[b]GSL*year = effect testing interaction between GSL and measurement year.

Least square means were used to separate periodic mean cubic foot per acre per year (PIA-CF) means among sapling GSL and time periods from 1963 through 2006. In the following table the true PIA-CF means (cubic feet per acre per year) and their standard error are displayed.

Sapling GSL	Period	Stand age yrs.	Least squares estimate	Sig. diff.	True values	
					Mean	Std. error
20	1963–1968	70	2.2548	g	9.53	0.77
20	1969–1973	75	2.7344	f	15.40	1.56
20	1974–1984	86	3.3243	def	27.78	1.70
20	1991–1985	93	3.6006	dc	36.62	1.70
20	1992–1993	95	3.4864	dce	32.67	5.34
20	1996–1998	100	3.5909	dc	36.27	3.62
20	2003–2006	108	3.3082	def	27.33	2.40
40	1963–1968	70	2.9196	ef	18.53	2.43
40	1969–1973	75	3.5381	dc	34.40	4.06
40	1974–1984	86	4.0012	bcd	54.67	3.98
40	1991–1985	93	4.1371	abc	62.62	2.15
40	1992–1993	95	3.7955	dc	44.50	3.50
40	1996–1998	100	4.0910	bcd	59.80	1.25
40	2003–2006	108	3.9231	bcd	50.56	5.44
60	1963–1968	70	3.3322	cdef	28.00	5.74
60	1969–1973	75	3.8126	bcd	45.27	6.23
60	1974–1984	86	4.193	abc	66.22	6.02
60	1991–1985	93	4.2026	abc	66.86	3.23
60	1992–1993	95	3.9512	bcd	52.00	4.93
60	1996–1998	100	4.1109	abc	61.00	6.76
60	2003–2006	108	4.1589	abc	64.00	7.60
80	1963–1968	70	3.4925	dce	32.87	5.74
80	1969–1973	75	3.7054	dc	40.67	3.04
80	1974–1984	86	4.1118	abc	61.06	5.33
80	1991–1985	93	4.3099	ab	74.43	3.08
80	1992–1993	95	3.9383	bcd	51.33	5.34
80	1996–1998	100	4.2664	ab	71.27	0.66
80	2003–2006	108	4.3737	ab	79.33	8.72
100	1963–1968	70	3.4532	dce	31.60	4.31
100	1969–1973	75	3.9383	bcd	51.33	7.37
100	1974–1984	86	4.1008	abcd	60.39	16.78
100	1991–1985	93	4.2760	ab	71.95	8.70
100	1992–1993	95	3.5927	dc	36.33	3.61

(Continued)

Table A23—(Continued).

Sapling GSL	Period	Stand age yrs.	Least squares estimate	Sig. diff.	True values Mean	Std. error
100	1996–1998	100	4.0650	bcd	58.27	3.70
100	2003–2006	108	4.2130	abc	67.56	2.60
120	1963–1968	70	3.4945	dce	32.93	4.02
120	1969–1973	75	4.0977	abcd	60.20	11.90
120	1974–1984	86	4.2268	abc	68.50	12.40
120	1991–1985	93	4.3634	ab	78.52	7.72
120	1992–1993	95	3.9703	bcd	53.00	5.92
120	1996–1998	100	4.2106	abc	67.40	5.38
120	2003–2006	108	4.5758	a	97.11	8.39

The analysis of variance table for periodic annual increment cubic volume (PAI-CF) for the pole plots.

Effect	Degrees of freedom	F Value	Pr > F
GSL[a]	5	71.43	<0.0001
GSL*year[b]	30	11.50	<0.0001
Year	6	4.80	<0.0001

[a]GSL= Growing stock level (i.e., 20, 40, 60, 80, 100, 120).
[b]GSL*year = effect testing interaction between GSL and measurement year.

Pole GSL	Period	Stand age yrs.	Least squares estimate	Sig. diff.	True values mean	std. error
20	1963–1968	70	2.9014	HI	18.20	3.64
20	1969–1973	75	3.4034	FGH	30.07	4.39
20	1974–1984	86	3.5727	EFGH	35.61	2.14
20	1991–1985	93	3.3884	FGH	29.62	2.90
20	1992–1993	95	3.1499	GHI	23.33	2.32
20	1996–1998	100	3.3696	FGH	29.07	0.64
20	2003–2006	108	2.8526	I	17.33	0.69
40	1963–1968	70	3.4232	FGH	30.67	1.75
40	1969–1973	75	3.7233	CDEFG	30.67	1.75
40	1974–1984	86	3.9608	ABCDEF	41.40	3.23
40	1991–1985	93	3.7810	BCDEFGH	52.50	3.24
40	1992–1993	95	3.4914	EFGH	43.86	5.38
40	1996–1998	100	3.7184	DEFGH	32.83	5.20
40	2003–2006	108	3.7376	BCDEFGH	41.20	1.40
60	1963–1968	70	3.6653	DEFGH	39.07	4.39
60	1969–1973	75	4.0254	ABCDE	56.00	4.54
60	1974–1984	86	4.2080	ABCDE	67.22	9.69
60	1991–1985	93	4.0629	ABCDEF	58.14	11.51
60	1992–1993	95	3.5410	EFGH	34.50	1.73
60	1996–1998	100	3.9690	ABCDEFG	52.93	10.16
60	2003–2006	108	4.0214	ABCDEFG	55.78	7.32

(Continued)

Table A23—(Continued).

Pole GSL	Period	Stand age yrs.	Least squares estimate	Sig. diff.	True values mean	True values std. error
80	1963–1968	70	3.6839	CDEFGH	39.80	5.89
80	1969–1973	75	4.0242	ABCDEFG	55.93	14.10
80	1974–1984	86	4.2252	ABCDE	68.39	11.98
80	1991–1985	93	4.2633	ABC	71.05	7.77
80	1992–1993	95	4.0043	ABCDEFG	54.83	7.67
80	1996–1998	100	4.1120	ABCDEF	61.07	5.78
80	2003–2006	108	4.2014	ABCDEF	66.78	19.99
100	1963–1968	70	3.8972	ABCDEFG	49.27	9.89
100	1969–1973	75	4.1474	ABCDEF	63.27	12.08
100	1974–1984	86	4.0851	ABCDEF	59.44	14.34
100	1991–1985	93	4.2499	ABCD	70.10	9.80
100	1992–1993	95	4.0043	ABCDEFG	54.83	9.33
100	1996–1998	100	4.0764	ABCDEF	58.93	11.23
100	2003–2006	108	4.2689	AB	71.44	4.30
120	1963–1968	70	3.7440	BCDEFGH	42.27	4.45
120	1969–1973	75	3.8754	ABCDEFGH	48.20	14.19
120	1974–1984	86	4.1675	ABCDEF	64.56	16.95
120	1991–1985	93	4.2293	ABCD	68.67	8.18
120	1992–1993	95	4.1405	ABCDEF	62.83	6.50
120	1996–1998	100	4.0395	ABCDEF	56.80	6.52
120	2003–2006	108	4.4466	A	85.33	10.30

Appendix B—Selected Tree and Stand Characteristics of Each of the 18 GSL Sapling and Pole Plots and for Each of the 3 Unthinned Sapling and Pole Plots

The GSL plots were measured 12 times from 1963 through 2014 and the unthinned plots were measured 7 times from 1978 through 2014. The Forest Vegetation Simulator (FVS) was used to summarize the data for each measurement and produce stand level metrics. These included: BA (square feet), TPA, stand density index (SDI), quadratic mean diameter (QMD, the diameter of the tree with the mean basal area), mean total tree height, total cubic feet volume (cubic feet per acre), merchantable cubic feet volume (cubic feet per acre, 9.0 inch d.b.h. and 6.0-inch top), and Scribner board foot per acre (Keyser and Dixon 2008; Dixon 2002; Wykoff et al. 1982). These data are displayed in figures 24–27, 32, 35–36, and 37 in the main text in RMRS-GTR-393.

All statistical inferences were determined using A Generalized Linear Mixed Model (GLMM) (Appendix A). The predictors include GSL, pole or sapling, year, thinning, and the GSL by pole or sapling interactions. The models incorporated a log-link function in order to account for nonnegative response distributions. A repeated measures temporal correlation structure was incorporated into all models using a radial smoother for each plot (Ruppert et al. 2003). Treatment-level comparisons between main and interaction fixed-effect levels were adjusted using Tukey's method determined using least squares means (Kramer 1956). Degrees of freedom were adjusted using the Kenward-Roger method (Kenward and Roger 1997). When necessary, an empirical sandwich covariance estimator was included in order to account for over dispersion (White 1982). All analyses were conducted using SAS PROC GLMMIX in Version 9.4 of the SAS System for Windows (Copyright © 2014 SAS Institute Inc.). Where appropriate two analysis tables are presented. One for the years 1963 through 2010, which did not include the unthinned plots. A separate analysis was conducted for the years 1978 through 2010 that included data from the unthinned plots. As a result, the significant grouping of similar least squares means were for the entire years of record and not just for any one given year.

Table B1—The following univariate statistics are included to fully disclose the extensive and robust analysis we used in reporting on a unique long-term study that Myers and Boldt (1961) began on the Black Hills National Forest and was brought to an end in 2014 by mountain pine beetles.

GSL	Year	Age	Trees/acre		SDI		BA/acre.		QMD		Height: feet		Total feet[3]		Merch. feet[3]		Board feet/acre	
		years	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*
Sapling plots																		
20	1963	65	110.7	1.33	22	0.88	22.3	0.33	3.7	0.12	26.7	0.88	66	4.9	0	0.0	0	0.0
20	1968	70	98.7	1.33	29	1.20	28.7	0.33	4.6	0.12	28.7	0.88	107	7.8	0	0.0	0	0.0
20	1973	75	70.7	2.67	40	1.76	40.3	0.88	5.7	0.17	31.7	0.67	191	16.1	0	0.0	0	0.0
20	1978	80	69.3	3.53	41	0.00	41.0	0.33	7.2	0.21	33.3	1.20	245	11.6	14	14.3	67	66.7
20	1984	86	69.3	3.53	56	0.00	56.0	0.33	8.8	0.26	36.3	1.76	415	22.6	156	49.0	667	196.4
20	1991	93	69.3	3.53	72	0.33	71.7	0.67	10.2	0.32	42.3	1.76	671	30.5	493	45.4	2053	148.5
20	1993	95	69.3	3.53	76	0.33	75.7	0.58	10.6	0.32	43.3	1.67	737	38.9	563	48.5	2293	188.1
20	1998	100	24.0	2.31	83	1.20	83.3	1.00	11.4	0.32	46.7	2.33	475	22.5	402	22.8	2547	408.1
20	2003	105	24.0	2.31	37	0.67	37.3	0.33	13.2	0.64	49.3	1.76	475	22.5	402	22.8	1920	180.4
20	2006	108	24.0	2.31	41	1.00	41.0	0.33	14.0	0.64	51.3	1.67	557	20.7	477	23.2	2320	100.7
20	2010	112	24.0	2.31	45	1.53	45.0	0.58	15.0	0.64	53.7	1.86	670	25.4	588	29.6	2840	92.4
20	2014	116	17.3	1.33	34	0.88	33.7	0.88	15.2	0.55	54.3	1.76	507	23.7	447	26.3	2187	66.7
40	1963	65	214.7	5.33	42	1.45	41.7	0.58	3.6	0.10	27.3	0.88	117	8.9	0	0.0	0	0.0
40	1968	70	206.7	6.67	58	2.00	58.0	1.00	4.5	0.00	29.0	1.00	205	6.6	0	0.0	0	0.0
40	1973	75	146.7	1.33	84	4.48	84.3	2.08	5.7	0.06	32.0	1.15	382	26.6	0	0.0	0	0.0
40	1978	80	146.7	1.33	85	1.86	85.3	1.20	7.1	0.09	35.3	0.88	503	24.0	13	6.7	53	26.7
40	1984	86	145.3	1.33	111	1.76	111.3	1.53	8.5	0.13	39.7	0.88	826	41.7	244	44.7	1093	231.3
40	1991	93	145.3	1.33	137	1.45	136.7	1.20	9.6	0.12	46.3	1.20	1269	56.7	819	82.6	3493	346.7
40	1993	95	145.3	1.33	142	1.45	142.3	1.15	9.8	0.12	47.0	1.00	1358	58.1	940	77.5	3960	360.0
40	1998	100	60.0	0.00	156	1.00	156.0	0.88	10.5	0.09	50.3	1.20	1094	79.4	862	25.0	4013	139.2
40	2003	105	60.0	0.00	81	1.33	81.3	0.67	12.1	0.12	52.3	1.20	1020	27.4	862	25.0	4013	139.2
40	2006	108	60.0	0.00	87	1.33	87.3	1.33	12.6	0.13	54.7	2.03	1172	37.0	997	42.3	4733	259.6
40	2010	112	60.0	0.00	96	1.86	96.3	1.00	13.4	0.13	56.3	1.45	1382	41.3	1188	38.7	5787	81.1
40	2014	116	33.3	13.53	54	20.74	54.0	12.45	13.7	0.27	57.0	2.52	776	265.6	672	223.3	3373	1134.3
60	1963	65	305.3	10.41	66	3.18	65.7	1.67	3.8	0.19	31.3	1.45	209	28.5	0	0.0	0	0.0
60	1968	70	304.0	10.58	89	5.55	88.7	3.28	4.6	0.23	33.3	2.60	348	56.9	0	0.0	0	0.0
60	1973	75	254.7	17.02	120	8.19	120.3	4.63	5.6	0.30	35.3	2.03	575	83.9	0	0.0	0	0.0
60	1978	80	222.7	11.39	121	4.98	121.3	3.46	6.9	0.38	38.0	1.73	737	92.3	46	46.0	227	226.7
60	1984	86	221.3	12.72	153	5.04	152.7	3.67	7.9	0.38	42.3	1.86	1128	105.6	258	129.7	1187	536.8
60	1991	93	221.3	12.72	181	4.06	181.3	3.18	8.9	0.38	48.0	2.00	1607	137.2	773	222.9	3480	1021.6
60	1993	95	221.3	12.72	187	3.53	186.7	2.85	9.0	0.35	49.0	2.08	1711	147.0	878	241.9	3947	1136.6

(Continued)

Table B1—(Continued).

GSL	Year	Age	Trees/acre		SDI		BA/acre.		QMD		Height: feet		Total feet^3		Merch. feet^3		Board feet/acre	
		years	$\bar{X}$	*SE*	$\bar{X}$	*SE*	$\bar{X}$	*SE*	$\bar{X}$	*SE*	$\bar{X}$	*SE*	$\bar{X}$	*SE*	$\bar{X}$	*SE*	$\bar{X}$	*SE*
60	1998	100	106.7	9.33	201	2.65	201.0	2.65	9.5	0.38	52.3	2.33	1411	75.0	1076	128.3	4853	618.1
60	2003	105	106.7	9.33	120	3.21	120.0	0.67	10.9	0.47	53.7	2.67	1411	75.0	1125	95.8	5040	500.1
60	2006	108	106.7	9.33	129	3.18	128.7	0.88	11.3	0.50	55.3	2.85	1603	97.8	1318	110.7	6093	553.5
60	2010	112	106.7	9.33	140	3.21	140.0	1.45	11.9	0.56	58.0	3.06	1893	116.8	1604	125.5	7600	794.3
60	2014	116	36.0	6.11	47	3.76	47.3	1.76	12.1	0.90	55.7	3.67	642	33.5	541	35.5	2587	265.7
80	1963	65	404.0	16.17	83	6.57	82.7	3.53	3.7	0.29	32.7	3.38	263	50.0	0	0.0	0	0.0
80	1968	70	382.7	15.72	104	8.67	104.3	4.51	4.4	0.33	37.3	3.28	417	74.4	0	0.0	0	0.0
80	1973	75	360.0	34.02	133	8.14	133.0	4.48	5.2	0.27	39.7	3.38	627	89.3	9	9.3	40	40.0
80	1978	80	300.0	23.09	145	5.67	144.7	3.21	6.4	0.34	42.0	3.79	878	110.0	57	32.3	267	150.3
80	1984	86	296.0	26.63	178	8.08	178.0	4.04	7.3	0.32	45.7	3.33	1263	112.0	231	105.3	1093	507.2
80	1991	93	296.0	26.63	212	9.02	211.7	4.48	8.2	0.34	51.7	3.38	1801	136.7	583	213.7	2747	1030.0
80	1993	95	293.3	29.06	217	10.48	217.3	5.04	8.4	0.39	51.7	2.96	1898	138.9	699	215.8	3267	1034.4
80	1998	100	157.3	11.85	233	11.26	233.3	4.91	8.8	0.35	55.0	3.21	1792	92.8	1059	272.9	4840	1318.8
80	2003	105	157.3	11.85	161	2.96	161.3	0.33	10.2	0.35	53.3	2.91	1792	92.8	1281	151.3	5867	732.6
80	2006	108	153.3	14.11	167	4.04	167.0	0.58	10.6	0.44	55.3	2.60	1978	87.6	1513	153.4	6920	803.0
80	2010	112	153.3	14.11	182	5.21	181.7	1.45	11.2	0.44	60.0	3.51	2372	113.3	1957	141.7	9107	818.6
80	2014	116	20.0	16.00	21	15.17	20.7	8.33	11.2	0.72	56.0	3.79	231	156.1	170	105.5	760	461.3
100	1963	65	497.3	14.67	108	2.40	108.3	0.67	3.9	0.03	34.3	2.03	360	24.8	0	0.0	0	0.0
100	1968	70	482.7	17.33	129	0.67	129.3	0.88	4.4	0.10	37.0	1.73	509	25.3	0	0.0	0	0.0
100	1973	75	425.3	39.82	164	4.36	164.0	2.73	5.2	0.22	39.0	1.53	769	53.9	0	0.0	0	0.0
100	1978	80	358.7	1.33	164	9.85	164.0	5.36	6.1	0.24	42.7	2.03	974	112.0	9	9.3	40	40.0
100	1984	86	356.0	2.31	197	13.43	197.0	7.94	6.9	0.30	46.7	2.19	1397	189.5	77	43.5	373	193.7
100	1991	93	356.0	2.31	229	13.35	228.7	8.14	7.6	0.26	51.7	2.67	1904	248.0	353	182.2	1707	907.0
100	1993	95	354.7	2.67	234	12.14	234.3	7.54	7.7	0.26	51.0	3.00	1971	242.0	438	177.0	2120	900.1
100	1998	100	230.7	12.72	247	8.96	247.0	5.78	8.0	0.20	54.0	3.00	2039	70.7	670	164.3	3307	925.6
100	2003	105	230.7	12.72	198	0.58	198.0	1.15	9.1	0.32	53.7	0.33	2039	70.7	1069	204.5	5147	966.7
100	2006	108	224.0	15.14	202	3.61	202.0	0.88	9.4	0.29	55.0	0.00	2171	39.6	1220	193.5	5827	877.7
100	2010	112	224.0	15.14	216	4.67	216.3	1.20	9.8	0.29	56.7	0.67	2479	34.0	1663	142.9	7733	607.7
100	2014	116	34.7	12.72	32	14.85	31.7	8.62	8.9	0.73	50.0	2.65	348	188.1	217	150.8	1000	688.6
120	1963	65	614.7	39.28	135	10.14	134.7	5.51	3.9	0.32	30.7	2.73	425	93.9	0	0.0	0	0.0
120	1968	70	596.0	34.02	158	10.09	158.3	5.55	4.4	0.35	34.0	3.06	581	110.2	0	0.0	0	0.0
120	1973	75	496.0	26.63	193	13.67	193.3	7.69	5.0	0.35	39.7	3.48	877	161.2	0	0.0	0	0.0
120	1978	80	465.3	32.03	194	9.61	194.0	5.84	5.8	0.41	41.3	3.38	1077	175.8	0	0.0	0	0.0
120	1984	86	453.3	32.85	231	12.17	231.0	7.37	6.6	0.38	45.0	3.46	1521	220.0	53	29.5	253	150.3

(Continued)

Table B1—(Continued).

GSL	Year	Age	Trees/acre		SDI		BA/acre.		QMD		Height: feet		Total feet^3		Merch. feet^3		Board feet/acre	
		years	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*	$\overline{X}$	*SE*
120	1991	93	452.0	32.08	266	11.98	265.7	7.31	7.2	0.38	50.0	4.04	2087	274.1	314	219.7	1653	1191.6
120	1993	95	449.3	34.74	271	12.22	271.0	6.93	7.4	0.38	51.0	4.04	2181	271.9	391	243.5	2067	1357.7
120	1998	100	298.7	15.72	288	12.17	287.7	7.26	7.6	0.38	54.0	4.36	2269	217.4	616	377.7	3240	2077.0
120	2003	105	298.7	15.72	238	2.65	238.0	3.21	8.7	0.36	52.3	2.19	2276	211.1	921	353.4	4467	1740.5
120	2006	108	277.3	11.39	231	16.50	230.7	10.17	8.9	0.35	55.3	1.67	2390	316.1	1116	395.2	5373	1940.2
120	2010	112	277.3	11.39	247	17.23	247.3	10.37	9.3	0.35	57.3	1.45	2722	336.1	1541	418.5	7307	1948.9
120	2014	116	86.7	42.35	70	36.10	70.0	18.98	8.2	0.55	52.3	2.03	703	380.1	294	219.5	1440	1082.5
Uthin	1978	80	608.0	46.01	277	21.84	277.3	10.00	6.1	0.03	32.3	3.21	2433	135.7	1298	20.3	6573	115.5
Uthin	1991	93	564.0	48.22	314	21.39	314.0	9.71	7.0	0.09	40.6	9.07	3227	283.2	1656	115.5	8373	766.8
Uthin	1998	100	521.3	54.57	310	22.93	310.3	9.85	7.2	0.12	38.4	3.48	3257	133.2	1773	115.3	9226	541.3
Uthin	2003	105	505.3	57.52	321	22.59	321.0	9.21	7.6	0.19	39.9	2.60	3443	133.4	1901	103.5	9787	507.2
Uthin	2006	108	462.7	38.94	295	6.24	295.0	2.31	7.6	0.30	40.8	2.19	3158	153.4	2009	260.5	10923	1284.2
Uthin	2010	112	462.7	38.94	307	4.04	307.0	2.19	7.8	0.33	40.7	1.20	3367	163.9	1962	281.6	10053	1374.9
Uthin	2014	116	121.3	48.95	43	16.05	42.7	6.56	5.4	0.45	38.7	3.48	267	74.3	69	45.5	360	249.8

To learn more about RMRS publications or search our online titles:

www.fs.fed.us/rm/publications

www.treesearch.fs.fed.us