GROWTH OF PONDEROSA PINE THINNED TO DIFFERENT STOCKING LEVELS IN THE WESTERN UNITED STATES

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ABSTRACT

Growth of ponderosa pine was studied by the western Forest and Range Experiment Stations of the USDA Forest Service in response to increasing demands for better and more precise estimates of yields possible through intensive management. We summarized results of 15 to 20 years of growth after thinning each of five stands to a wide range of stocking levels. The stands—two in the Black Hills of South Dakota, and one each in northern Arizona, central Oregon, and northern California—ranged in size from small saplings to large poles and in age from about 20 to 90 years. Within the fundamental constraints of site quality, thinning influenced growth markedly and, on the better sites, stands were more responsive to manipulation than they were on poorer sites. Only the most general conclusions are possible; nevertheless, results at every installation demonstrated the marked decline in volume production and, conversely, the rapid attainment of merchantable-sized material at low residual stand densities.

INTRODUCTION

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is one of the most widely distributed pines in the Western United States. Within this vast area of contrasting soils and climate, many studies of thinning in even-aged stands of ponderosa pine have been conducted over the years (Gaines and Kotok 1954; Mowat 1953; Myers 1958). In general, results from these early studies were similar to those found from thinning most pure even-aged stands, in that diameter growth was greater in lightly stocked than in heavily stocked plots. But other results seemed contradictory. Sometimes total cubic-foot volume production increased with increasing stand density and sometimes it did not. Results from studies conducted in one part of the range seemed to have limited use in another part. Dissimilar experimental designs and measurements that were incomplete or based on specific products further restricted comparability. Also, these early studies did not test the low reserve densities that may be desired for today's multiresource management.

Growth information was needed over a wide range of stand and site conditions, and with a minimum of operational restrictions, to provide useful guides for a variety of management objectives. To fill this need three western Forest and Range Experiment Stations of the U.S. Department of Agriculture, Forest Service, cooperated through the use of a common study plan (Myers 1967).

This paper reports 15- to 20-year results of this West-wide study. It describes some of the relationships between stand growth and the stand attributes of basal area, mean diameter, and site.

ORIGINAL STUDY PLAN

Five areas within the range of ponderosa pine in the Western United States were arbitrarily selected for study and assigned to the participating Experiment Stations (fig. 1). These five "provinces" differ in many respects. Physiography ranges from the uplift of the Black Hills of South Dakota to the Coconino Plateau of Arizona, the Cascade Range of Oregon, and Sierra Nevada of California. Two varieties of ponderosa pine are recognized (*P. ponderosa* var. *ponderosa* and var. *scopulorum*). Some provinces are without summer precipitation; other provinces receive most of their annual precipitation during the growing season.

Within each province, four tree-size classes in even-aged stands from small saplings to large poles, as available, were to be sampled. To be sampled within each size class were areas of low, medium, and high site quality for that province.

The initial plan specified that each study installation consist of three replicates of six arbitrarily selected plots thinned to six different stand densities. Plots were to be at least 0.25 to 0.5 acre with 20-ft isolation strips for small saplings, and 0.5 to 1.0 acre with 30-ft isolation strips for the larger size classes.

One plot in each replicate was to be thinned to the density considered best for that site index, based on past experience. Two or three plots were to be thinned to lower, and two or three plots to higher stand densities. The highest stand density was chosen such that the production of merchantable material would be reduced below that of lower densities. And the lowest density level was chosen such that cubic-foot volume production would be lower than that at higher densities.

Stand densities to be retained after thinning were specified as a series of growing stock levels (GSL's) (Myers 1967). These levels were defined by relationships between basal area and average stand diameter. Numerical designation of the level assigned to a plot was the basal area per acre that would remain after thinning when mean stand diameter was 10 inches or more. Stands with trees smaller than 10 inches when thinned would contain residual basal areas that were less than the designated GSL.

Thinning was to be from below, primarily, the smallest trees and rough dominants being removed. Each

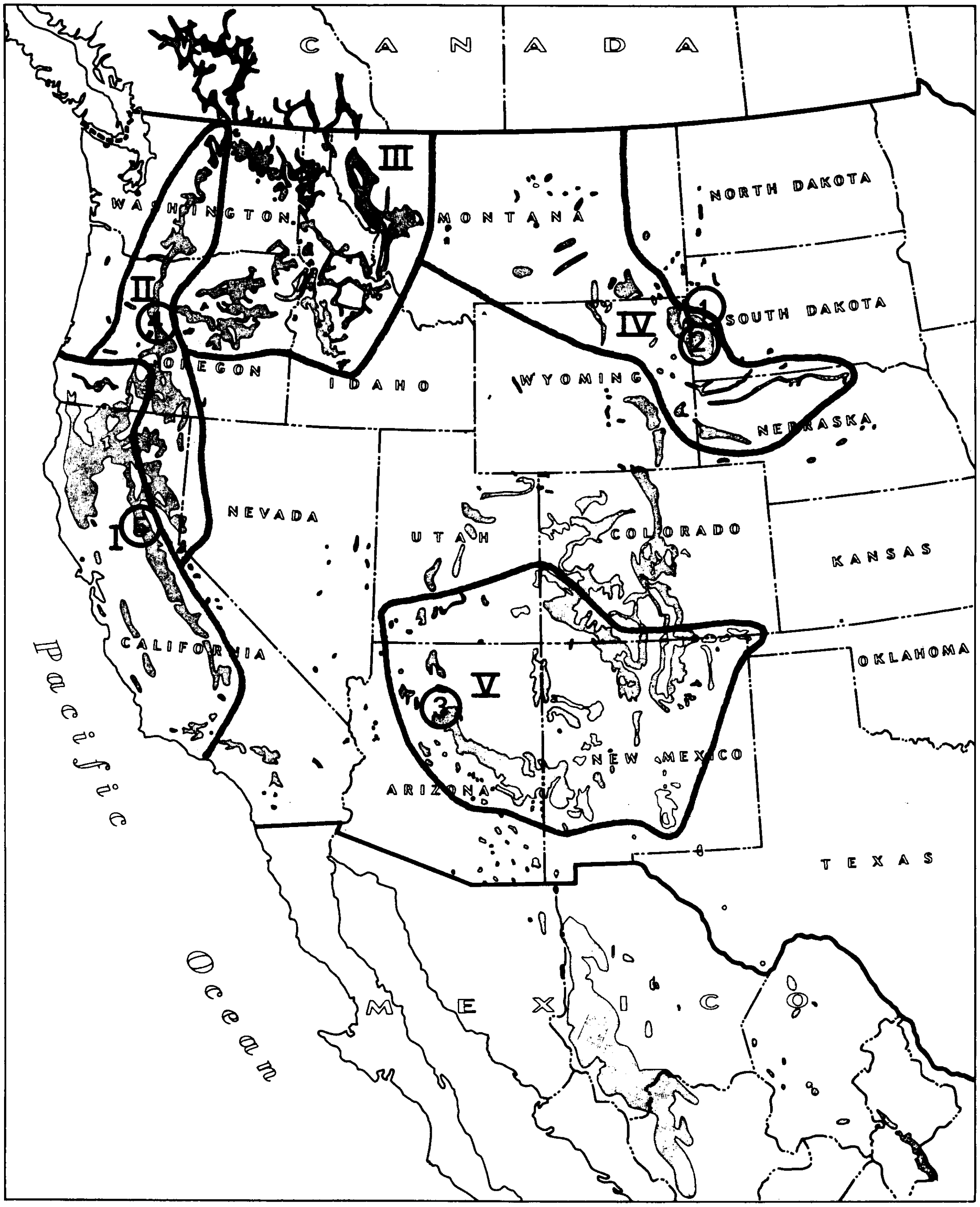

Figure 1—Province boundaries (Roman numerals) and installation locations (Arabic numerals) for study of levels of ponderosa pine growing stock. (1) Black Hills saplings, (2) Black Hills poles, (3) Taylor Woods, (4) Lookout Mountain, (5) Elliot Ranch (map of botanical range of ponderosa pine from Curtis and Lynch 1957).

installation was scheduled to run for 20 years, with measurements at 5-year intervals. At the end of 10 years, plots were to be rethinned to the specified GSL's.

Before the growing season following initial thinning, all trees were to be tagged, described by crown class, and measured for diameter at breast height (d.b.h.) to the nearest 0.1 inch. Tree damage and diseases were to be noted. Various sampling schemes could be used to select trees for total height and height to the living crown, measured to the nearest 1 ft, and total stem volume when measured by optical dendrometer. All measurements were to be repeated on the same trees after each 5-year period.

THE INSTALLATIONS

The study as envisioned was ambitious, requiring prodigious amounts of land, labor, and money. Cooperators experienced difficulty both in finding large enough areas of uniform site and stand conditions, and in allocating sufficient resources to sample but a few of the province/size/site combinations. Although many fewer than planned, the four installations established in naturally regenerated stands and one in a plantation (Elliot Ranch) nearly spanned the geographic range of ponderosa pine (fig. 1). Characteristics of the installations are summarized in table 1.

The five installations were established in general conformance with the plan except those at Elliot Ranch and Lookout Mountain. At Elliot Ranch only five GSL's were tested because of limited stand area, and plots were rethinned to prescribed GSL's at 5- rather than at 10-year intervals because of rapid growth. At Lookout Mountain height to the living crown was not measured. Remarkably, all installations have been maintained, many for as long as 20 years. Detailed descriptions of the installations and measurements taken at Taylor Woods (Ronco and others 1985), Lookout Mountain (Barrett 1983), and Elliot Ranch (Oliver 1979) are available. Measurement standards and procedures followed at the Black Hills installations were similar to those described by Ronco and others (1985) for Taylor Woods.

ANALYSIS

Mean tree and stand characteristics for each plot at each measurement were calculated as follows:

- D.b.h.—quadratic mean diameter at breast height
- Total height—calculated for tree of mean diameter by using measured tree heights in each plot or treatment in an equation relating total height to d.b.h.
- Basal area—square feet per acre
- Percent live crown—calculated as 100 [(total height - height to live crown)/total height]
- Total volume—cubic-foot volume inside bark from ground line to tip, estimated for each tree from gross volume equations for the Black Hills (Myers 1964) and for Taylor Woods (Hann and Bare 1978). At Lookout Mountain and Elliot Ranch where an optical dendrometer was used, equations relating volume to d.b.h. were calculated separately for each treatment.

Linear regressions of 5-year periodic annual increments (PAI's) for treatment means of diameter, height, and basal area and total volume per acre were used to describe trends. For percent live crown, the equation was based on that characteristic at the end of the period. Independent variables were stand basal area and mean d.b.h. at the beginning of the period, site index, and several of their transformations. Although stand treatment was based on GSL, stand basal area was used in modeling because of variations in stand diameter and marking practices among plots assigned similar GSL's at Taylor Woods (Ronco and others 1985). We did not attempt to analyze merchantable volume production because utilization standards varied widely among installations.

Selection of independent variables was by conventional stepwise regression with coefficients calculated by ordinary least squares. Criteria for selecting variables or their transformations that best explained the variation in PAI's were these: the statistics F, coefficient of determination (R^2), and standard error (S); those with fewest terms; and those that were consistent with known biological relationships. The synthesis of these criteria necessarily caused the choice of variables to be partially subjective.

The calculated variances are underestimates of the actual amounts. The chief reasons are that we used treatment means for each period in this summary analysis rather than plot means. We did not account for serial correlations within installations caused by repeated measurements. For the height and volume equations, measurements were not uniform among the installations. Furthermore, because only one installation usually was available for analysis within each province/site quality combination, the influence of province (or location or stand history among other influences) could not be separated from the influence of site quality.

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

Province	Name	Year installed	Site index[1]	Size class	Growing stock levels	5-year periods analyzed
IV	Black Hills	1964	57	large saplings	20,40,60,80,100,120	4
IV	Black Hills	1964	57	small poles	20,40,60,80,100,120	4
V	Taylor Woods	1962	62	small poles	30,60,80,100,120,150	4
II	Lookout Mt.	1966	92	large poles	30,60,80,100,120,150	3
I	Elliot Ranch	1970	140	large poles	40,70,100,130,160	3

[1]Meyer 1938.

RESULTS AND DISCUSSION

Diameter

Periodic annual diameter growth was strongly correlated with site index and stand basal area, and less so with mean d.b.h. (fig. 2A). Growth increased exponentially as site index increased. This curvilinear form fit the data better than the linear form, but we suspected this may have been an artifact of the data. The installation at Elliot Ranch with the highest site index was the youngest by 20 years, and was expected to grow more rapidly in diameter than would older stands. Nevertheless, when the stepwise re-gression procedure was run on the data without Elliot Ranch, exponential site index was still a better fit than was linear site index. Exponential site index alone explained 43 percent of the observed variation in diameter growth. As expected, diameter growth declined curvilinearly as reserve stand basal area increased. This commonly reported relationship, which explained an additional 28 percent of the variation, was strong at every installation.

Treatments with larger trees tended to grow more rapidly in diameter than treatments with smaller trees. Although the variation explained by mean d.b.h. (an additional 4 percent) was less than it was for site index and stand basal area, mean d.b.h. was significant. The resulting equation was:

$$PAI\ DBH = 0.3135 + 0.0965 \exp(SI/100) - 0.0994 \ln BA + 0.0102\, DBH$$

$$R^2 = 0.749$$

$$SEE = 0.1 \text{ inch}$$

where

PAI DBH = periodic annual increment of d.b.h. in inches

exp = base of natural logarithms

SI = site index (Meyer 1938) in feet at 100 years total age

ln = natural logarithm

BA = stand basal area at the beginning of the period in square feet per acre

DBH = quadratic mean stand d.b.h. at the beginning of the period in inches

R^2 = coefficient of determination

SEE = standard error of the estimate.

Height

Site index was the overwhelming influence on periodic annual height growth of the average tree. The relationship

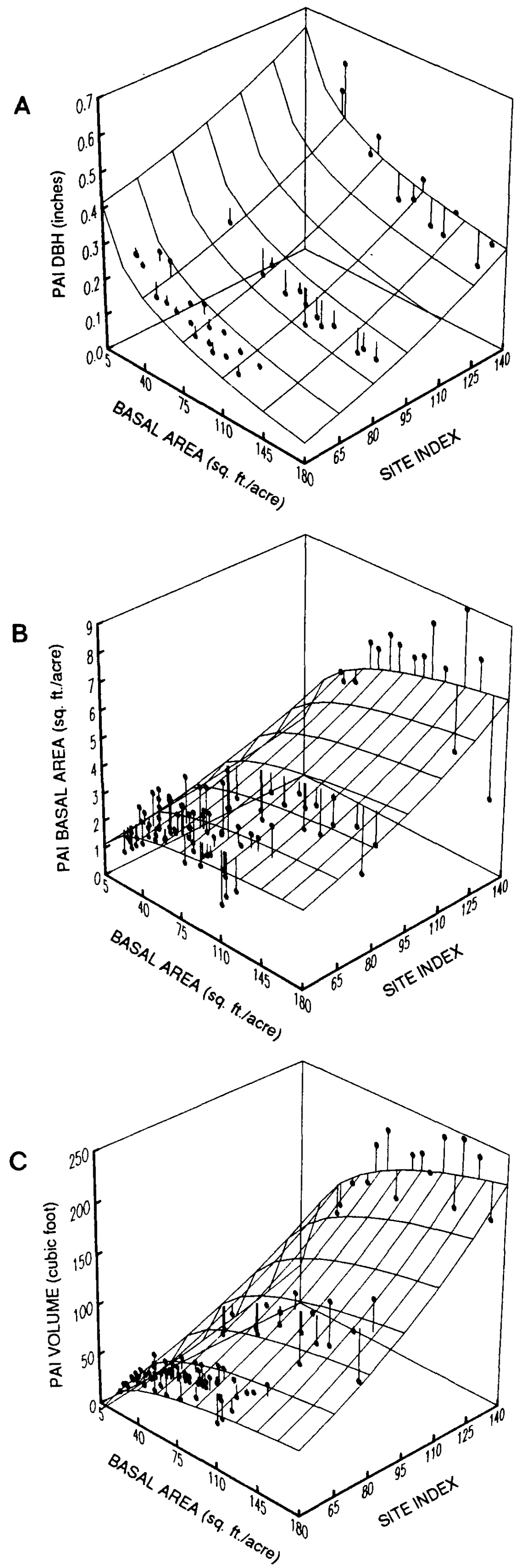

Figure 2—Stand density and site index were related to periodic annual increments (PAI) of (A) diameter and (B) basal area for stands10 inches in diameter, and (C) volume of even-aged ponderosa pine.

was curvilinear and positive, and explained 93 percent of the variation observed across all installations. Additional variation could be explained by mean stand d.b.h. and basal area at the Elliot Ranch installation only. We expected that, within an installation, plots with more basal area would tend to have smaller trees, on the average, and less growth in mean height than would plots with less basal area. Only at Elliot Ranch was this expectation borne out, probably because of the much more rapid height growth in this young, high-site plantation than was found in the other installations. Although the additional variation explained by mean stand d.b.h. and basal area was small (about 2 percent), these variables were included to make the equation for the combined data more generally applicable:

$$PAI\,HT = -0.6731 + 0.6329\exp(SI/100) + 0.0348\,DBH - 0.0016\,BA$$

$$R^2 = 0.942$$

$$SEE = 0.1 \text{ foot}$$

where

PAI HT = periodic annual growth in total height in feet.

A more intriguing and important question, however, is whether stand density influenced the height growth of dominant or future crop trees. We could not answer this question because we restricted analysis to treatment averages only.

Basal Area

Net periodic annual basal area growth was related significantly with site index and to a lesser extent with stand basal area. Both relationships were positive and curvilinear (fig. 2B); PAI basal area increased exponentially with increasing site index and logarithmically with stand basal area. Basal area growth differences were larger among stand density treatments in installations on better sites than they were in installations on poorer sites. Thus, the cross product of the transformed variables of site index and reserve stand basal area seemed to fit the combined data:

$$PAI\,BA = 1.4884 + 0.3742\ln BA\,[\exp(SI/100)] - 0.2404\,DBH$$

$$R^2 = 0.683$$

$$SEE = 0.9 \text{ ft}^2 \text{ per acre}$$

where

PAI BA = net periodic annual basal area increment in square feet per acre.

Mean stand diameter was related, significantly, with PAI basal area, explaining an additional 11 percent of the observed variation. Stands with larger mean diameters tended to grow more slowly in basal area than stands with smaller mean diameters. This negative relationship is to be expected from this data set because plots in all installations were rethinned at least once (twice at Elliot Ranch). Thinning from below raised the mean stand diameter, more so when thinning to low reserve stand basal areas. Trees in plots with low basal areas grew faster in diameter. Hence, plots with low reserve stand basal areas, which grew less basal area, tended to have larger mean diameters than plots with high reserve basal areas.

Total Volume

Similar to PAI basal area, PAI total cubic-foot volume was strongly related to site index and somewhat less to stand basal area. The relationship was positive and curvilinear for both variables (fig. 2C). Again similar to PAI basal area, stand basal area exerted a greater influence on PAI volume on better sites than it did on poorer sites. As a result the cross product of exponential site index and the logarithm of reserve stand basal area described the observed variation in volume growth:

$$PAI\text{ Volume} = -40.4050 + 12.4336\ln BA\,[\exp(SI/100)]$$

$$R^2 = 0.904$$

$$SEE = 16.9 \text{ ft}^3 \text{ per acre}$$

where

PAI Volume = net periodic annual increment in total stem volume from ground to tip inside bark in cubic feet per acre.

Mean stand diameter was a significant variable. And, similar to its relationship to PAI basal area, was negatively correlated. But in this case, its contribution to explained variation was of no practical importance—less than 1 percent.

After plots were rethinned back to the prescribed GSL's, volume production tended to be lower than it was during the period after initial thinning. Mortality after the second thinning tended to reduce volume production, especially at the higher GSL's at Elliot Ranch and the Black Hills polesize stands. However, at lower GSL's where mortality was insignificant, production was lower as well. This decline in PAI volume with time was expected because stands at all installations had passed the culmination of period annual increment (Meyer 1938).

Percent Live Crown

The proportion of a tree's total height in living crown is recognized as an indication of its competitive position within the stand and its ability to grow. Percent live crown would be expected, therefore, to be related to stand basal area. Because percent live crown changes slowly in response to changes in stand density, most investigators studying short-term thinning response report no change in percent live crown. We found no relationship between percent live crown and stand basal area for the first 5 years after initial thinning, and only a weak relationship for the first 10 years. Only after 10 years did the relationship to stand basal area become strong.

To describe the influence of stand basal area on percent live crown, we included only the 15- and 20-year measurements and expressed percent live crown as that existing at the end of those measurement periods. We found percent live crown to be strongly correlated with stand basal area. As basal area increased percent live crown decreased, rapidly at first and then more slowly throughout the range of stand basal areas tested. This curvilinear relationship can be described adequately with the equation:

$$PLC = 92.138 - 7.673 \ln BA$$

$$R^2 = 0.545$$

$$SEE = 4.0 \text{ percent}$$

where

PLC = mean proportion of the trees' total height in living crown expressed as a percentage.

Stepwise regression analysis of the combined data indicated a strong influence of site index. It was not included in the above equation, however, because its influence appears to be an artifact of the data. No live crown measurements were recorded at Lookout Mountain—the installation of intermediate site quality. For a given stand density, live crowns averaged 8 percent higher at the Elliot Ranch plantation (site index 140) than crowns in the natural stands in the Black Hills and at Taylor Woods (average site index 60). But this difference might be the result of differing stand origins, or differences in any number of other stand and tree attributes, as well as differing site indexes.

CONCLUSIONS

The reader is cautioned not to draw firm conclusions from the results obtained from the combined data. The data obtained from each installation are of uniformly high quality, and results and conclusions drawn from them are sound. In combining the data, however, we assumed that treatment response differences among installations were caused by site quality differences. Even though this assumption enabled us to produce models that behaved according to accepted biological theory, we suspect that the factors we combined under the variable of site index, which are discussed below, had some measurable effect.

The five installations were scattered over a vast geographic area of contrasting soils and climate, and included two varieties of ponderosa pine (*P. ponderosa* var. *ponderosa* and var. *scopulorum*). Some of the genetic differences may have affected wood production. The five installations did not sample equally the range in site indexes—three installations were on about site index 60, one on site index 92, and one on site index 140. And, finally, sampling schemes, particularly for height and volume, differed among the installations.

Nevertheless, what we called site index seemed to perform credibly in integrating and explaining these immense and complex differences. A contributing reason for the good performance of site index may have been that stockability was not a problem. All installations were chosen on sites capable of the productivity estimated by Meyer (1938). Of the transformations tested, exponential site index, which from experience would be expected to fit the data well, was, in fact, the best fit of those transformations we tested.

Despite thinning to a wide range of stand densities from open-grown to densities high enough to jeopardize stand health, observed growth differences were correlated best by exponential site index. It, alone, explained from 43 percent for PAI d.b.h. to a high of 93 percent for PAI height. The axiom that productivity of the site is the key factor underlying growth is supported by these results.

Within the fundamental constraints of site quality, thinning influenced markedly all the growth measures we examined. For production of basal area and volume the relationship was curvilinear and, on better sites, stands were more responsive to thinning than they were on poorer sites. These relationships were in accordance with our expectations.

Considering our small sample, all conclusions must be considered tentative, and conclusions about long-term stand performance could be especially misleading. Stand age is known to have a strong effect on stand density-growth relationships. Several conclusions about intermediate management of even-aged stands are possible, however. The volume-growth relationship (fig. 2C) demonstrates the significant decline in production with the low residual stand densities often required to meet multiresource management constraints. For instance, stands with site index 60 grew only 43 ft^3 per acre of volume annually when thinned heavily to 40 ft^2 of basal area per acre, whereas, 66 ft^3 could be achieved if these stands were thinned to 110 ft^2. Comparison growth rates for stands on site index 140 land were 145 ft^3 (thinned to 40 ft^2/acre) and 197 ft^3 (thinned to 110 ft^2/acre). Conversely, the diameter growth relationship (fig. 2A) demonstrates that if a goal of management is to produce merchantable-sized material rapidly, then lower residual stand densities are desirable. Computing diameter growth for the same sites and stand densities as above, we found that 5-inch d.b.h. stands grew 0.10-inch faster in diameter when thinned heavily than when thinned to a moderate density, regardless of site quality. At the lower site indexes, more than one precommercial thinning was required for the higher reserve densities. This points to longer thinning intervals and, perhaps, to the desirability of lower reserve stand densities, at least for initial thinnings.

As originally conceived with all the size/site/province combinations sampled, this study could have provided the data for constructing variable density yield tables. Today's growth and yield computer programs offer versatility impossible to achieve from static tables and, if based on temporary sample plots in existing stands, are cheaper and faster to construct, as well. We know of no substitute, however, for remeasurement data from planned treatment response trials such as these five installations provide. These data are invaluable for precise estimates of biological relationships and for validating computer simulated growth predictions for a given set of conditions and treatments.

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Speakers answered questions from the audience following their presentations. Following are the questions and answers on this topic:

Q. (from Carl Beyerhelm)—Open-grown ponderosa pine often are shorter and fatter than adjacent trees grown with competition. This indicates that height growth benefits from competition. How do you square this with your contention that height growth is not related to stand density?

A.—Contrary to appearances, intertree competition has not been found to stimulate height growth of conifers. Rather, competing trees maintain a fairly constant height growth at the expense of diameter growth, thus giving the appearance of being taller than trees of the same age in the open. Only when stands are extremely dense (higher than densities found in "normal" yield tables) can height growth be affected. If this were not so, the site index concept for measuring site productivity would not work.

Q. (from Carl Beyerhelm and Bill Coburn)—At what stand density level can one expect the best "value" growth of ponderosa pine, given that the more open spacings encourage branch retention and hence grade reduction?

A.—I don't believe that stand density management is an effective method of improving the value of ponderosa pine logs. The species does not readily shed dead branches. And branch diameters are noticeably reduced only at spacings so close that merchantable volume production is sacrificed (spacings of 6 by 6 ft in one study). Probably pruning, interest in which has picked up lately, is the only answer, and then only in intensively managed stands on good sites.