Effects of Stand Density on Top Height Estimation for Ponderosa Pine

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Site index, estimated as a function of dominant-tree height and age, is often used as an expression of site quality. This expression is assumed to be effectively independent of stand density. Observation of dominant height at two different ponderosa pine levels-of-growing-stock studies revealed that top height stability with respect to stand density depends on the definition of the dominant height. Dominant height estimates calculated from a fixed number of trees per acre (ranging from 10 to 60 of the tallest trees per acre) were less affected by density than those calculated from a proportion (with the cutoff ranging from 95th to the 70th percentile) of the largest trees in the stand.

Keywords: site index, growth and yield, dominant height

The potential for tree volume production of forested lands is linked to numerous factors. Many are difficult to quantify. Availability of water and nutrients, growing season length, temperature, and solar radiation all contribute to productivity. An effective and often-used surrogate for these factors is site index, a productivity index derived from tree heights. Site index has been used widely in forest types across North America and is still used for many western conifers, including ponderosa pine (Pinus ponderosa P.&C. Lawson). Curtis et al. (1974) defined site index as follows: “Site quality of even-aged stands is usually expressed as site index—average height of some specified stand component at a specified reference age.” The average height referred to by Curtis may be referred to as the site height, top height, or dominant height, and the definition thereof is not standardized. The average may or may not be weighted, and the specified stand component is quite variable.

The various methods of estimation for a given definition of top height are often biased (Rennolls 1978), and varying plot size from the defined plot size imposes some level of bias (Garcia 1998, 2005, Magnussen 1999).

A primary usage for site index has been in modeling stand yields over time (e.g., DeMars and Barrett 1987, Hann 2009). In such implementations, errors in site index estimates are costly, as estimates of forest yield over time form the basis for decisionmaking with regard to both evaluating short-term treatment response and long-term forest planning.

Site index, expressed as a function of dominant height and stand age, is typically assumed to be static and unaffected by other factors. Top height has been suggested to have a “lack of sensitivity” to thinning from below (Assmann 1970), and some have noted the potential for density-induced changes in dominant height growth or site index (Dunning 1942, Baker 1953).

Ponderosa pine is a widely distributed and highly valued timber species, and numerous site curves have been published (e.g., Meyer 1938, Lynch 1958, Powers and Oliver 1978, Barrett 1978, Hann and Scrivani 1987). These equations are developed for specific geographic regions, to account for any changes in height growth patterns that may exist within the range of the species.

Although the effects of density on average height of ponderosa pine have been demonstrated (Peracca and O’Hara 2008), research results on site index and top-height growth have been inconsistent. Lynch (1958), using a paired-analysis procedure, detected a significant density effect for ponderosa pine site index in the inland northwest. However, Minor (1964) did not detect any density effect in establishing site index curves for northern Arizona. In a study of height growth for southern Oregon (Ritchie and Hann 1990), growth equations forecast reductions in potential height growth of up to 10% for ponderosa pine trees in a dominant crown position (a crown ratio greater than 60% and crown closure at the top of the tree less than 5%), suggesting the potential for a density effect on growth and, thus, dominant height. With regard to other species, Alexander et al. (1967) presented adjustments for site index in lodgepole pine (Pinus contorta Dougl. ex Loud.) and more recently, Flewelling et al. (2001) developed Douglas-fir (Pseudotsuga menziesii [Mirbel] Franco) site index equations with adjustments for stand density during the early stages of stand development. Pienaar and Shriver (1984) found no consistent response in dominant height growth to variations in planting density of slash pine (Pinus elliottii Englem.).

One of the difficulties with top height is that the definition involves order statistics that can be sensitive to definition of top height (Rennolls 1978). One aspect of this sensitivity is the effect of plot size on top height estimation. Reductions in plot size produce underestimates of top height (Garcia 1998, Sharma et al. 2002, Mailly et al. 2004). Another potential problem area is the true degree of independence of top height from density management.

The intent of this study was to examine the influence of density management on top height and seek definitions to minimize any density influence. We examined the relationships between various...
expressions of top height and stand density in two ponderosa pine levels-of-growing-stock (LOGS) studies (Oliver 2005), one on a highly productive site in northern California and the other on a marginally productive site in northeastern Oregon.

Methods

Application of Site Index

Quantifying the effects of density management on top height is complicated by the existence of multiple definitions. Numerous approaches have been specified for ponderosa pine (Table 1). As noted by King (1966), the method of tree selection and sample size determination are key elements to consider when estimating site index. Several methods have been proposed (Rennolls 1978). One approach is guided by a fixed proportion (e.g., King 1966), where some proportion of trees, sorted by size, are selected. In the case of King (1966), this recommendation was for the largest 10 out of 50 (20%). Yet another approach is to select a sample guided by a number of trees per acre (e.g., Powers and Oliver 1978). Some definitions used for ponderosa pine are difficult to evaluate because of either a lack of specificity (e.g., some number of dominant trees) or the absence of a specified area. We used both methods in evaluating ponderosa pine top height.

Study Sites

Data were obtained from two of the six installations of the west-wide ponderosa pine LOGS study (Oliver 2005): the Elliot Ranch and Crawford Creek sites. The ponderosa pine LOGS study design specified that each installation would consist of three replications of plots thinned to five or six different stand densities. Plots sizes for the study ranged from 0.25 to 0.5 ac in size, with 20-ft isolation strips for small saplings, and from 0.5 to 1.0 ac, with 30-ft isolation strips, for the larger size classes. For both Elliot Ranch and Crawford Creek, plot size was specified as 0.5 ac, although adjustments were made to this at Crawford Creek.
At Elliot Ranch, plots were thinned to target densities in 1969, 1974, 1979, and 1989. Plots have been remeasured at 5-year intervals. At each measurement period, breast height diameter (dbh) was observed for each tree. At the beginning of the experiment, total tree height was subsampled at each measurement period. However, in the 2004 measurement, heights were measured on all 557 living trees.

At the time of establishment, it was thought that the Elliot Ranch site was of uniform productivity. However, it was later determined that the installation is on a boundary between two different soil types that vary in productivity. Seven of the plots are classed in the Cohasset series, and eight are in the Horseshoe series or unclassified alluvium. The Horseshoe series appears to be slightly less productive than the Cohasset series (Oliver 1997). A correction was established by averaging across a number of different selections of dominant trees, ranging from the tallest in the plot to the tallest 10–20 per acre. Differences ranged from 6 to 10 ft, with an average of 8 ft. For this analysis, we applied an 8-ft adjustment to the average heights in the Cohasset series plots to correct for the soil variability within the installation. There appears to be little chance of confounding with treatment, as the split among treatments for the two soil series was remarkably even; all GSLs were present in both soil series, and mean GSL for each series differed very little (difference in mean GSL = 9).

Crawford Creek

The Crawford Creek installation is located at 44° 36′ N latitude, 118° 26′ W longitude in the Blue Mountains of eastern Oregon, at an elevation of 4,400 ft. Annual precipitation averages 21 in., falling mostly as snow with accumulations to 2 ft (Cochran and Barrett 1995). The Crawford Creek site is in a natural stand of ponderosa pine, with an understory of scattered western larch (Larix occidentalis Nutt.) seedlings and saplings occurring in the most open plots. Unlike Elliot Ranch, the plots are grouped in three geographically distinct blocks of six plots. Treatments were randomly assigned within each of these blocks. Initial treatments were applied in 1967. At establishment, the stand was approximately 60 years old (total age); at the time of the 2004 measurement, the stand was approximately 97 years old, just below the base age of 100 for central Oregon ponderosa pine (Barrett 1978). The tallest tree observed at Crawford Creek was 95 ft. The GSLs for Crawford Creek were 30, 60, 80, 100, 120, and 140. The plots were thinned to target density in 1967, 1977, and 1986.

Plots were remeasured at approximately 5-year intervals until the last measurement in 2004. At each measurement period, dbh was recorded for each tree and heights were subsampled. In the 2004 remeasurement, tree height was observed for all trees on all but one of the plots. On one of GSL-140 plots, approximately half the trees were selected for height measurements. Total number of living trees in 2004 for all plots was 1,385, with height observed on 1,299 (94%) in the 2004 measurement. Heights were predicted using a locally derived height-diameter equation for the 86 trees with missing heights in the GSL-140 plot.

Plot size for 13 of the Crawford Creek plots was 0.5 ac, and the remaining 5 were 0.4 ac. Evidently this adjustment to the study design was done to save time, because the densest plots (GSL 140 and 120 at Crawford Creek) had many trees. This variation in plot size within Crawford Creek will have some effect on the variability and will tend to cause some degree of underestimation of top height relative to the 0.5-ac plots. As with Elliot Ranch, larger tree size is associated with lowest levels of growing stock in the most recent measurement (Table 3). Recent mortality, primarily from mountain pine beetle (Dendroctonus ponderosae) has been high in the high-GSL plots (120 and 140) at Crawford Creek, resulting in a net loss in basal area in the 1999–2004 growth period.

### Analysis

As top height definitions vary both in methods and level of specificity across published site index systems, we considered a range of possible definitions. We considered six different methods of calculating a top height for each plot using three different definitions of tree size (height, dbh, and $dbh^2 	imes height [dbh^2ht]$) and two different quantities for ordering (percentile and stems per acre):

1. Mean height of the largest $p$ percentile of the height distribution.
2. Mean height of the largest $n$ stems per acre of the height distribution.
3. Mean height of the largest $p$ percentile of the diameter distribution.
4. Mean height of the largest $n$ stems per acre of the diameter distribution.
5. Mean height of the largest $p$ percentile of the $dbh^2ht$ distribution.
6. Mean height of the largest $n$ stems per acre of the $dbh^2ht$ distribution.

In each case, trees were selected only if they did not demonstrate top damage, excessive lean, or history of bark beetle activity. Application of $dbh^2ht$ may be considered as a basal-area-weighted height distribution or as a surrogate for the volume distribution. Because of the subjectivity involved, we did not consider any methods derived from a field determination of dominance.

We fit a simple linear model for various definitions of top height:

$$\text{top height}_{ijk} = \beta_{0ijk} + \beta_{1ijk} \text{GSL} + \epsilon$$

(1)

with 2 selection methods ($i = 1, 2$: trees per acre and percentile), three sorting keys ($j = 1–3$: height, $dbh$, $dbh^2ht$) and six different levels of selection ($k = 1, 2, \ldots, 6$). The limits were specified as the largest 10, 20, 30, 40, 50, and 60 trees per acre and the 70th, 75th, 80th, 85th, 90th, and 95th percentiles.

Relative height, defined here as the ratio of mean height of a selection method for dominant trees divided by the maximum observed height for the site, was plotted over the percentile of the distribution chosen and over the number or proportion of trees (Figures 1–4).
Results and Discussion

It is axiomatic that the more trees selected from a sorted list (largest to smallest) will produce progressively lower estimates of top height and drive down estimates of site index derived from this top height. This is confirmed in the plots of relative height (Figures 1–4), where the steepest part of the curve is usually at the lowest

Figure 1. For Elliot Ranch, each sample plot’s relative height (top height divided by maximum observed height) is plotted over selection by percentile at growing stock levels (40–160) for selection by height (a), selection by dbh (b), and selection by $\text{dbh}^2 \times \text{height}$ (c).

Figure 2. For Elliot Ranch, each sample plot’s relative height (top height divided by maximum observed height) is plotted over selection by trees per acre by growing stock levels (40–160) for selection by height (a), selection by dbh (b), and selection by $\text{dbh}^2 \times \text{height}$ (c).

Figure 3. For Crawford Creek, each sample plot’s relative height (top height divided by maximum observed tree height) is plotted over selection by percentile at growing stock levels (30–140) for selection by height (a), selection by dbh (b), and selection by $\text{dbh}^2 \times \text{height}$ (c).

Figure 4. For Crawford Creek, each sample plot’s relative height (top height divided by maximum observed tree height) is plotted over selection by trees per acre by growing stock levels (30–140) for selection by height (a), selection by dbh (b), and selection by $\text{dbh}^2 \times \text{height}$ (c).
levels of selection (fewer than 20 trees per acre or the 10th percentile). In Figures 1–4, a flat line is indicative of a lack of sensitivity to selection intensity, whereas a steep or erratic trend suggests that small changes in the number or percentage of trees selected may have a great impact on resulting top height and site index estimates.

Stability of any top height metric with regard to the number of trees selected is a desirable feature, as it implies robustness in a derived site index estimate. At Crawford Creek, selecting by percentile produced fairly steep slopes (Figure 3), although this trend was less pronounced at Elliot Ranch (Figure 1). These curves tend to be steeper for percentile selection at the highest densities because when selecting by percentile from a dense plot, a small change in percentile selected involves a greater number of trees than the same percentile from a more open stand. By the same token, in the more open stands, the same change in percentile selected represents fewer trees and has less influence on top height.

The relationship between top height and trees per acre or percentile selected by the tallest trees is monotonic (e.g., Figure 1a), whereas section by dbh or dbh²ht can produce erratic trends, particularly at the low selection intensity levels (e.g., Figure 1b and 1c).

Tables 4 and 5 present the results of linear fits over GSL. The probability levels (P values) test the hypothesis that the slope of the line relating top height to GSL is zero. Thus a significant probability level is evidence of some degree of top-height instability across varying levels of density, using an assumed linear relationship. The actual magnitude of the slope is expressed as a value labeled Δ, which is the estimated change in top height (ft) associated with an increase in density of 100 GSL. This Δ value is just below the maximum observed effect on top height conditioned on the range in values of this study.

Fits for top height at Elliot Ranch presented in Table 4 reveal a reduction in top height of approximately 4.4 ft for an increase in GSL of 100 when top height is defined as the 10 tallest trees per acre. However with a P value of 0.08, this is of marginal statistical significance. In general, selecting by trees per acre at Elliot Ranch appears to provide top height estimates that are fairly stable across a range of densities. Changes in top height for a change of 100 GSL range from −4.4 to +3.3 ft within a range of the tallest 10 to tallest 60 trees per acre, and none of these are significant departures from zero at the 5% level.

Similarly, selecting by largest diameter trees per acre at Elliot Ranch shows a range of GSL effects from −4.0 ft to 2.6 ft, and again, none of these values is statistically different from zero at the 5% level. In contrast, selection by a proportion of the distribution of heights at Elliot Ranch results in top height values that change more with density (ranging from −8.6 to −13.8 ft when selecting by height), and these values are all highly significant (all P values <0.01). Selecting by a proportion of dbh or dbh²ht produces similar results. The tradeoff is in the intercept value (I-40 is the intercept translated to top height at a minimum GSL of 40). In other words, for any given level of density, the top height values are less sensitive to proportional selection than selection by trees per acre. So if top height of the most open stands is considered a true achievable top height, then there is a distinct tradeoff between selection by proportion and selection by trees per acre.

At Crawford Creek, the general trends are the same, although top height values are much lower. However, the range of top height values for selection by trees per acre trends more strongly negative (a greater effect of increasing density on decreasing top height). The range of values here is −4.2 ft to −8.1 ft, and one must also consider that because Crawford Creek is a less productive site, these top height responses as a proportion of total height are greater than those observed at Elliot Ranch. As the number of trees selected for top height estimation increases, the probability levels tend to increase using trees per acre on both sites. As long as enough trees are selected (about the 20 largest per acre), one would expect top height values to be fairly robust for a wide range of density values on a good site such as Elliot Ranch, and perhaps less so for a poorer site such as Crawford Creek.

When trees are selected using a proportion of the distribution, density is generally highly statistically significant, and the estimate of Δ is large relative to that observed when selection is by trees per acre (Table 4).

The difference in sensitivity to selection method between the two sites appears to be a result of a greater range of heights for any given definition of dominance at Elliot Ranch, because thinnings were executed from below at both sites.

It should be noted that sensitivity to changing the number of the largest trees per acre defining top height was high at Elliot Ranch.
and relatively low at Crawford Creek. At Elliott Ranch, the more productive of the two sites, there was greater within-plot variability in tree heights among the larger trees. SD of height of the 40 tallest trees per acre, for example, was consistently higher for Elliott Ranch than Crawford Creek.

If resulting estimates of site index are indeed affected by density management, then what effect might this have on management? First, if site index is being used to drive growth models, it may lead to underestimated height growth and volume response to density management. The degree is difficult to determine, as it will depend on the particular growth models and the linkages between diameter and height growth. Second, it is possible to underestimate the value of unmanaged stands, as the true potential site index may be higher than that observed. In comparing two ponderosa pine stands with the same estimated site index, one with density management and one without, the unmanaged stand will have the greater capacity for productivity as indexed by height, because site index is effectively underestimated in the unmanaged stand.

Finally, although there are no standards for the way in which top height is defined, we find that the definition itself may overwhelm any concerns for the effects of density. For example, a site index value derived from a definition of the largest 10 trees per acre is not comparable to one derived from the largest 40 trees per acre. Therefore, a consistent definition for top height in ponderosa pine is important for comparable site index estimates.

Conclusions

In general, we found that top height in ponderosa pine decreased with increasing stand density. If resilience to changes in density is desired, then selection by trees per acre rather than percentile should be favored. At the most productive site, the effect of changes in GSL appeared to be most influential for selection by percentile whereas this trend was less pronounced at the poorer site.

Similarly, with lower productivity, selection by trees per acre minimized the GSL effect on top height estimation. Selection of dominant trees by a percentile of the size distribution appeared to be sensitive to density and may be inadvisable if site index estimations are required across a range of densities.

Selecting by tree height tends to produce the highest values of top height. However, it would appear that if top height is defined with a limit between the largest 20–40 trees per acre, the distinction between sorting by diameter, height, or basal-area-weighted height are relatively small.

For comparative purposes, site index estimates should be accompanied by the specification of top height, and comparisons of ponderosa site index without a clear definition of top height should probably be avoided.

Literature Cited


