
A Density Management Diagram for Even-aged Ponderosa Pine Stands

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ABSTRACT: We developed a density management diagram (DMD) for ponderosa pine using Forest Inventory and Analysis (FIA) data. Analysis plots were drawn from all FIA plots in the western United States on which ponderosa pine occurred. A total of 766 plots met the criteria for analysis. Selection criteria were for purity, defined as ponderosa pine basal area $\geq 80\%$ of plot basal area, and even-agedness, as defined by a ratio between two calculations of stand density index. The DMD is relatively unbiased by geographic area and therefore should be applicable throughout the range of ponderosa pine. The DMD is intended for use in even-aged stands, but may be used for uneven-aged management where a large-group selection system is used. Examples of density management regimes are illustrated, and guidelines for use are provided. *West. J. Appl. For.* 20(4):205–215.

Key Words: Silviculture, stand density index, stocking diagram, northern goshawk, mountain pine beetle.

Density management diagrams (DMD) are simple graphical models of even-aged stand dynamics. They are based on relations incorporating fundamental assumptions about density-dependent behavior of populations including competition, site occupancy, and self-thinning. A critical distinction between DMDs and stocking charts (e.g., Edminster 1988) is that DMDs include top height which, along with site index, allows estimates of age and growth (Drew and Flewelling 1979, Jack and Long 1996).

The most common application of DMDs is in determining what postthinning density will result in the type of stand desired at the next entry (Farnden 2002). They are also extremely useful in displaying and evaluating alternative density management regimes. For example, a Rocky Mountain lodgepole DMD (McCarter and Long 1986) has been used to display and evaluate density management regimes for such diverse objectives as reducing susceptibility to mountain pine beetle attacks (Anhold et al. 1996) and maintaining ungulate hiding cover (Smith and Long 1987).

We describe the construction of a DMD for even-aged ponderosa pine (*Pinus ponderosa* Laws.) stands in the western United States. Our analysis included examination of

possible regional variations in the relations used in DMD construction. Use of the ponderosa pine DMD is illustrated with several management examples.

Development

Database

The data used in construction of the DMD were drawn from USDA Forest Service Forest Inventory and Analysis (FIA) surveys completed between 1980 and 2002. Survey data from all states in which ponderosa pine occurs were obtained from the FIA database website (FIADB) (Miles et al. 2001; www.ncrs2.fs.fed.us/4801/FIADB). Twenty-six surveys from 14 states had ponderosa pine occurring on at least one plot. This data set, therefore, includes both *P. ponderosa* var. *ponderosa* and var. *scopulorum* (Conkle and Critchfield 1988). Because 1995 FIA surveys have used a mapped plot design (Conkling and Byers 1993), meaning that two or more conditions (e.g., stand types or ages, or forest and nonforest cover) could be present on a plot, we considered the FIA condition, rather than the entire plot, as the sample unit to maintain homogeneity among subplots. For each condition, the proportion of the plot occupied by that condition is recorded in the FIA inventory. For example, an FIA plot using a four-subplot mapped design might have three subplots located in a mature stand (condition 1) and one subplot located in an adjacent clearcut (condition 2). The data for the plot would show a condition proportion of 0.75 in condition 1 and condition proportion of 0.25 in condition 2. Using this method, we obtained a total of 8,183 conditions for use as potential (i.e., at least one ponderosa

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pine present) study plots (Table 1). The term “plot” will be used hereafter as a synonym for the FIA condition.

We obtained the following variables from the FIA database for trees >1.0 in dbh: state, county, plot number, species, diameter, height, trees per acre (expansion factor), and individual tree cubic-foot volume. FIA data include volume on a per tree basis that is calculated using local volume equations (Miles et al. 2001). We calculated total number of trees, cubic-foot volume, and basal area on a per acre basis for ponderosa pine and for all other species combined. Mean height, maximum height, and mean height of the tallest 40 trees per acre (HT40) were determined using individual tree heights and number of trees per acre. Stand density index (SDI; Reineke 1933) was calculated using the quadratic mean diameter and summations methods (SDI_{Dq} in Equation 1 and SDI_{sum} in Equation 2).

$$SDI = \left(\frac{Dq}{10}\right)^{1.6} \cdot TPA \quad (1)$$

where SDI is stand density index, *Dq* is quadratic mean diameter in inches at breast height, and TPA is the number of trees per acre.

$$SDI = \sum \left(TPA_j \cdot \left(\frac{D_j}{10}\right)^{1.6} \right) \quad (2)$$

where *D_j* is the diameter (in inches) of the *j*th tree in the sample, and TPA_{*j*} is the number of trees represented by the *j*th tree.

The two methods have been shown to produce values of SDI that are essentially equal for even-aged stands, but increasingly divergent with increasing skewness of the diameter distribution (Long and Daniel 1990, Shaw 2000, Ducey and Larson 2003). Ducey and Larson (2003) quantified the relationship between SDI_{sum} and SDI_{Dq} using a Weibull model and showed that the ratio of the two values approaches 1 for stands that are even-aged (i.e., diameter distribution weighted heavily about the mean diameter). Therefore, we calculated the ratio of SDI_{sum}:SDI_{Dq} for the purpose of separating relatively even-aged stands from stands with more complex structures.

Crown width data were not collected during most of the surveys from which we obtained our data, so we used crown width data from another study (Shaw in review). We modeled crown width using Equation 3 to relate crown width to dbh for 1,419 individual ponderosa pine trees. Trees were included in the data set if they were currently in an open-grown condition as indicated by a stand-level SDI of less

than 100 (i.e., <25% SDI_{max}; see discussions of maximum SDI and threshold of competition below). It is possible that some portion of the trees included in crown width analysis may have been grown under more dense conditions (e.g., prior to thinning or insect infestation), but the results of sensitivity testing suggested that the effect of such trees on the crown width model was probably minimal. The model has an estimated *R*² of 75% and standard error of 1 ft.

$$CW = 0.27 + 1.87 * dbh^{0.82} \quad (3)$$

where CW is crown width in feet.

Plots with only dead trees (e.g., recently burned or cut plots) or with missing values were eliminated from consideration. Plots with a condition proportion <0.5 were also removed to ensure that the plot was based on a minimum of two subplots and reduce the chance that a high blow-up factor would produce unusual values on a per-acre basis. We also eliminated plots with quadratic mean diameters <2.0 in. Plots with fewer than 25 trees per acre were excluded because relatively few (<5) trees were measured on these plots (for example, under current FIA plot design 4 tally trees scale to 24 TPA). In an effort to draw plots from nearly pure, nearly even-aged stands for analysis, we applied two additional filtering criteria: (1) ponderosa pine basal area >80% of total plot basal area, and (2) SDI_{sum}:SDI_{Dq} > 0.95.

Stand variables were analyzed and plotted in various combinations in an effort to identify unusual conditions and outlying values. Only seven additional plots were eliminated because of unusual values (e.g., impossibly high SDI). The final number of plots retained for analysis was 766, located in all states within the United States range of ponderosa pine except North Dakota (Table 1 and Figure 1).

These plots were identified by geographic location: (1) Northwest; (2) Northern Rockies; and (3) Southwest (Figure 1). The boundaries between these areas are similar to boundaries drawn by Conkle and Critchfield (1988) in their analysis of ponderosa pine genetics. For example, the boundary between the Northern Rockies and Southwestern regions appears to correspond to different proportions of monoterpene components and frequency of two-needle fascicles (Conkle and Critchfield 1988).

Our filtering criteria eliminated plots disproportionately among states and across the range of ponderosa pine (Table 1 and Figure 1). We attribute this to characteristics of composition and structure that tend to be regional in nature. For example, in California, where we retained less than 1%

Table 1. FIA surveys and number of plots on which ponderosa pine occurs.

State (no. surveys)	PP plots	Plots used	State (no. surveys)	PP plots	Plots used
Arizona (3)	1,685	161	New Mexico (2)	1,157	58
California (1)	481	3	Nevada (1)	12	1
Colorado (2)	434	53	Oregon (2)	884	103
Idaho (1)	918	50	South Dakota (3)	493	78
Montana (1)	945	157	Utah (2)	281	30
North Dakota (2)	3	0	Washington (1)	444	13
Nebraska (3)	184	4	Wyoming (2)	262	55

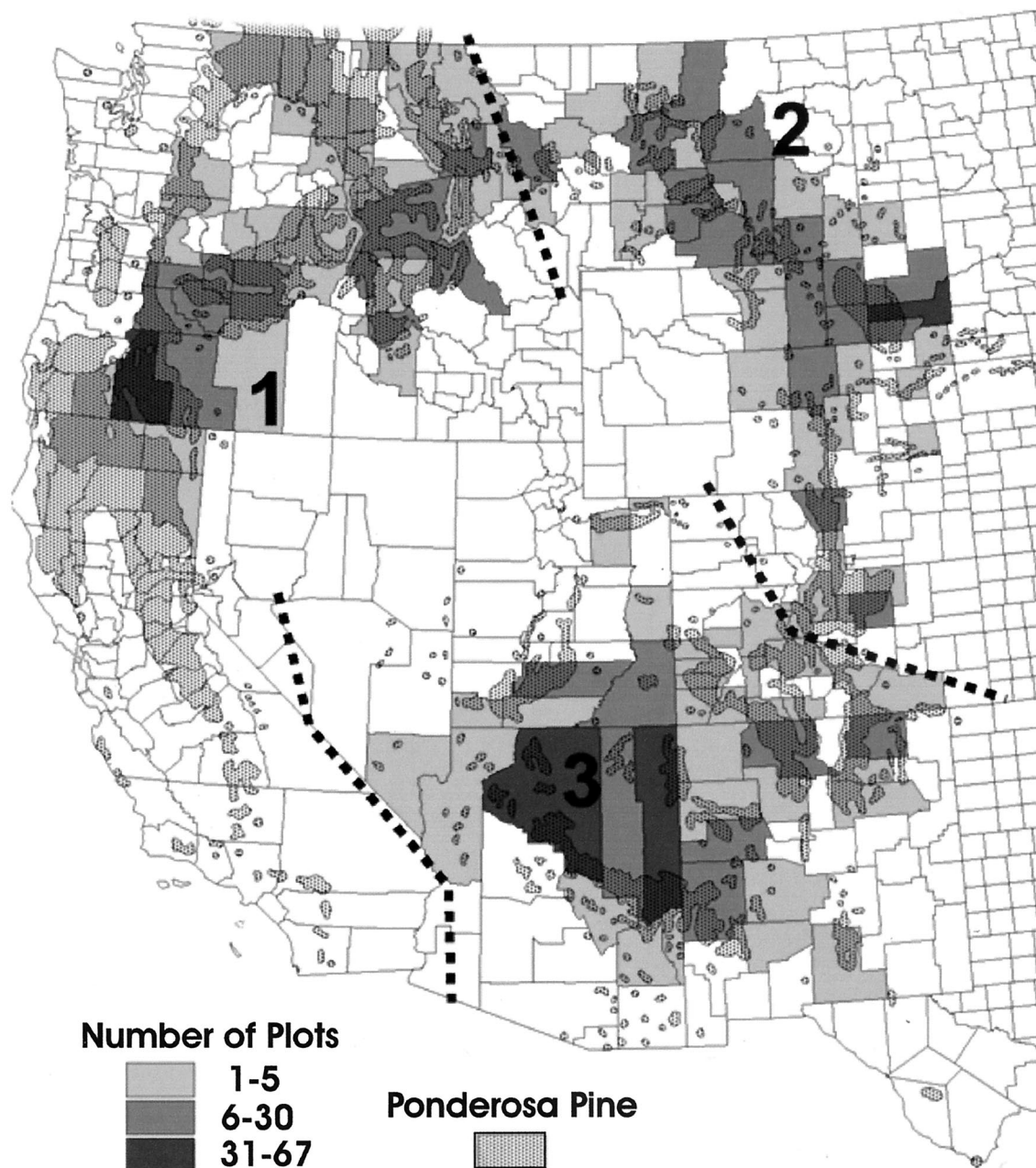


Figure 1. Range of ponderosa pine and number of analysis plots by county.

of the original plots, ponderosa pine commonly occurs in mixed-conifer stands with multiple age classes (Helms 1994). In contrast, many ponderosa pine stands in South Dakota (particularly the Black Hills), where we retained 42% of the original plots, tend to be relatively pure and even-aged (Shepperd and Battaglia 2002). We will discuss later the effect of plot distribution and other characteristics of the database on applicability of the density management diagram.

Construction of the Diagram

Density management diagrams have been constructed using several different formats (Jack and Long 1996). We have chosen (Figure 2) the format introduced by McCarter and Long (1986), with Dq and TPA on the major axes and relative density represented by SDI (Equation 1). We prefer

this format over, for example, one with mean stem volume instead of mean diameter, because most of the potential users of the diagram are familiar with SDI and find it easier to visualize mean diameter than mean stem volume. SDI, like other size-density indices of relative density, is particularly useful for characterizing stand dynamics (e.g., site occupancy, level of growing stock, and competitive interaction) because it is largely independent of stand age and site quality (Curtis 1982, Jack and Long 1996).

We calculated SDI using the exponent of 1.6 (Equation 1). Other estimates for the size-density exponent for ponderosa pine range from 1.66 to 1.77 (Oliver and Powers 1978, DeMars and Barrett 1987, Edminster 1988, Cochran et al. 1994). While they are of considerable ecological

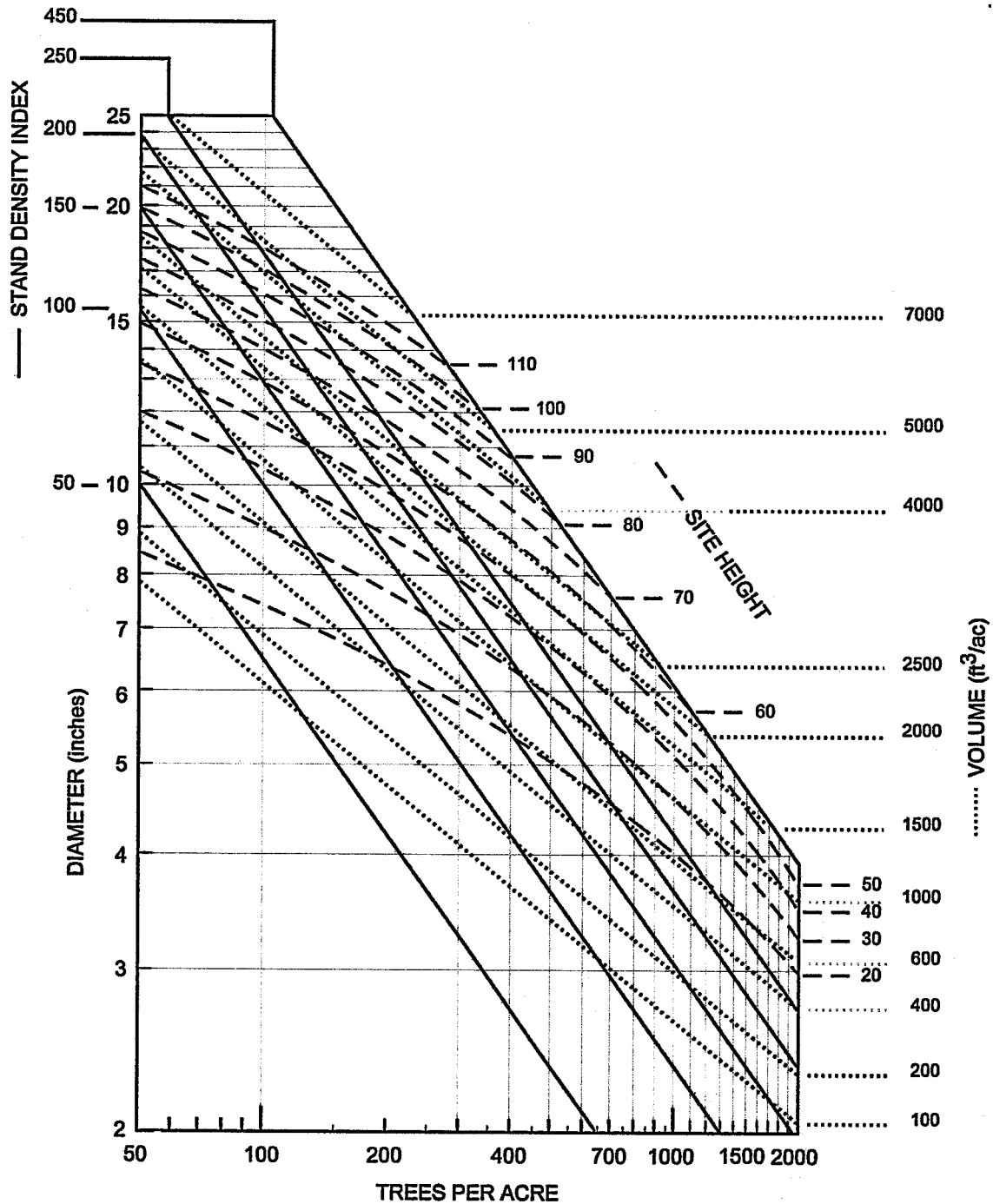


Figure 2. A density management diagram for even-aged ponderosa pine stands.

interest, we contend that these differences in the exponent are not of great importance from a practical, silvicultural standpoint.

For ponderosa pine, we assume 450 to be a reasonable approximation of the maximum size-density relation, i.e., the theoretical boundary for combinations of mean diameter and density. There are various estimates of the maximum SDI (SDI_{max}) for ponderosa pine. Some of these are actually estimates of “average maximum density” (AMD); AMD is the average SDI (SDI_n) of self-thinning stands and is assumed to be about 80% of SDI_{max} . Estimates of ponderosa

pine SDI_{max} used by the USDA Forest Service range from 429 (Pacific Southwest Region) to 450 (Intermountain, Northern, Rocky Mountain, and Southwest Regions). The largest SDIs represented in our data set are about 400 (Figure 3).

A key feature of DMDs are lines representing top or site height (i.e., the average height of the “site trees,” the dominants and codominants used in estimating site index). Equation 4 was fit with nonlinear regression to relate Dq to TPA and HT40. The model has an estimated R^2 of 73% and a standard error of 0.1 in. Examination of the residuals (e.g.,

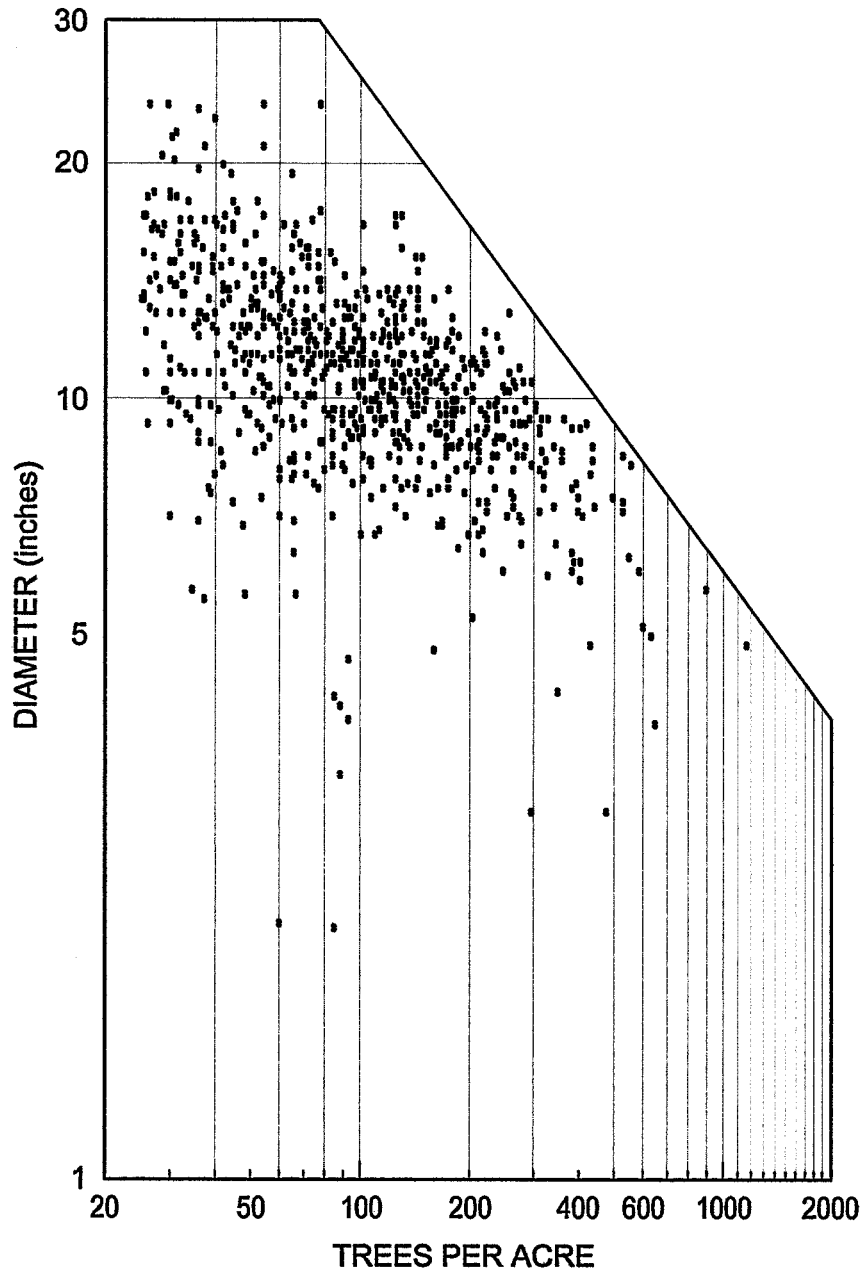


Figure 3. Dq and TPA for the 766 plots included in the analysis data set.

Figure 4) revealed that the model is unbiased with respect to the predictor variables as well as site index, SDI, volume, and basal area; it is also unbiased with respect to geographic location. When Equation 4 is used to generate height lines for the DMD, HT40 tends to be somewhat underestimated when Dq is small (e.g., <10 in.).

$$Dq = 2.07 + (202 - 200 * TPA^{0.0011}) * HT40^{0.64} \quad (4)$$

Another set of lines, representing total stand volume (VOL), was generated using a nonlinear regression model (Equation 5) relating VOL, Dq , and TPA. The model has an estimated R^2 of 91% and a standard error of 10 ft³/ac. Examination of residuals suggests that the model is essentially unbiased with respect to the predictor variables as well as site index, SDI, and basal area. As with Equation 4, there

were no apparent biases associated with geographic origin of the data. Residual analysis does suggest VOL may be somewhat underestimated when HT40 is greater than 100 ft.

$$VOL = -152 + 0.017 * TPA * Dq^{2.8} \quad (5)$$

where VOL is gross cubic-foot volume per acre.

Based on analysis of residuals, the basic relationships captured in the diagram appear to be essentially independent of site quality and geography. Therefore, there appears to be no reason to construct separate regional ponderosa pine density management diagrams. The ranges of the Dq and TPA axes and the HT40 and VOL lines were chosen to approximate the range of values represented in our data set (e.g., Figure 3).

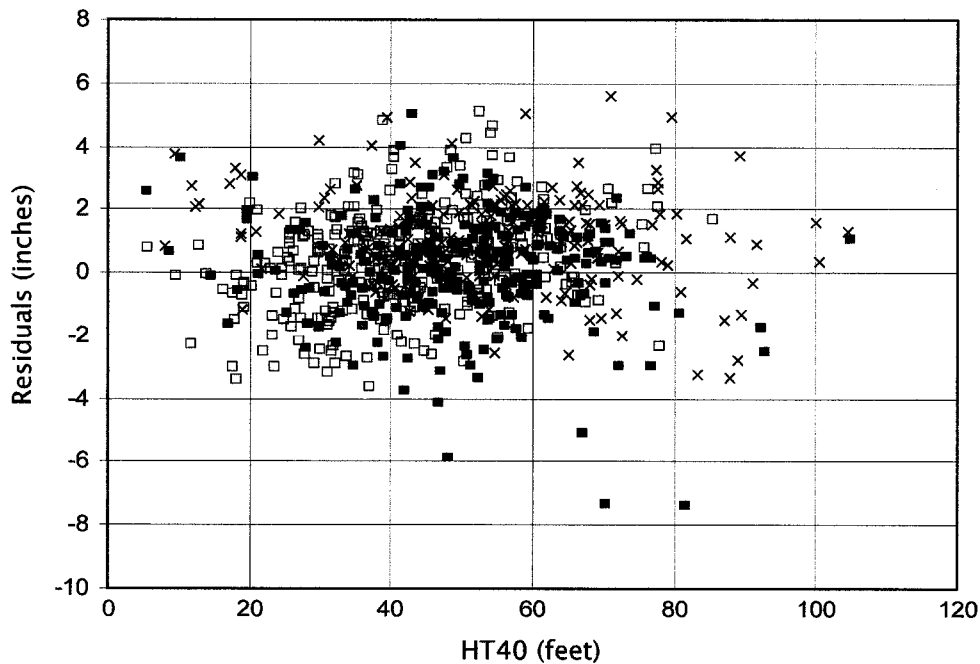


Figure 4. Residuals for predicted Dq plotted against HT40 (Equation 4). Symbols correspond to geographic regions in Figure 1 (x, Northwest; □, Northern Rockies; ■, Southwest).

SDI_{max}

The DMD includes an SDI_{max} equal to 450 (Table 2). DeMars and Barrett (1987) and Cochran et al. (1994) suggest, in general, that the SDI of “normal” or “fully stocked” (SDI_n) ponderosa pine in northeast Oregon and southeast Washington is 365. SDI_n does not correspond to our SDI_{max} , but rather to the average SDI of self-thinning populations. In general, SDI_n is thought to be about 80% of SDI_{max} and, therefore, the 365 estimate of SDI_n corresponds to an SDI_{max} of 456, i.e., essentially 450.

Some research suggests maximum SDIs that are lower than 450. For example, Edminster (1988) analyzed data from over 4,000 relatively even-aged (i.e., with fairly narrow ranges of dbhs) ponderosa pine stands from the central and southern Rockies and found that for the 2% of the stands with the highest relative densities, the average SDI was 419. Powell (1999) suggests a unique SDI_{max} for each plant association in the Blue Mountains of Oregon.

Lower Limit of Self-Thinning

We suggest that the 250 SDI line on the DMD represents the lower limit of the self-thinning zone (characterized as the zone-of-imminent-competition-mortality by Drew and Flewelling 1979). As a percent of SDI_{max} , 250 is nearly 60%, a figure that has generally been associated with the onset of self-thinning (Long 1985). For even-aged pon-

derosa pine in Oregon and Washington, self-thinning is observed to be low when SDI is less than 250 but substantial at SDIs greater than 250 (e.g., Cochran and Barrett 1998, 1999).

Crown Closure and the Competition Threshold

In terms of relative density, 25% of SDI_{max} has generally been associated with the transition from open-grown to competing populations (Long 1985). Therefore, we suggest that the 100 SDI line on the DMD be used to represent the onset of competition.

Initial crown closure, the point at which crowns just begin to touch, has for various species been associated with the onset of competition (e.g., Drew and Flewelling 1979, Long and Smith 1984, Jack and Long 1996). That does not appear to be the case for ponderosa pine. Assuming square spacing, the crown width-dbh relationship for open-grown trees (Equation 3) suggests that crown closure in even-aged ponderosa pine stands will be associated with an SDI of 250–290 or at least 60% SDI_{max} . The implication is that crown closure is not associated with the onset of competition, but rather the onset of self-thinning.

Full Site Occupancy

We propose 150 as a reasonable estimate of the lower limit of full site occupancy for ponderosa pine (Table 2). Relative densities in the range of 35–40% SDI_{max} have been suggested as appropriate for capturing “near maximum” stand growth (Long 1985, Marshall et al. 1992, Jack and Long 1996). Cochran and Barrett (1998) examined 35 years of growth data from thinned and unthinned even-aged ponderosa pine stands, and their analysis suggests that SDIs >150 (i.e., 33% of our proposed SDI_{max}) should capture at least 70% of potential gross volume growth (of course, when $SDI < 250$, gross and net volume growth are expected to be virtually identical).

Table 2. Suggested indicator SDIs for ponderosa pine.

Stand development event	Percent of maximum	Approximate SDI
Maximum	100	450
Lower limit of self-thinning	55–60	250
Lower limit of “full site occupancy”	35	150
Onset of competition	25	100

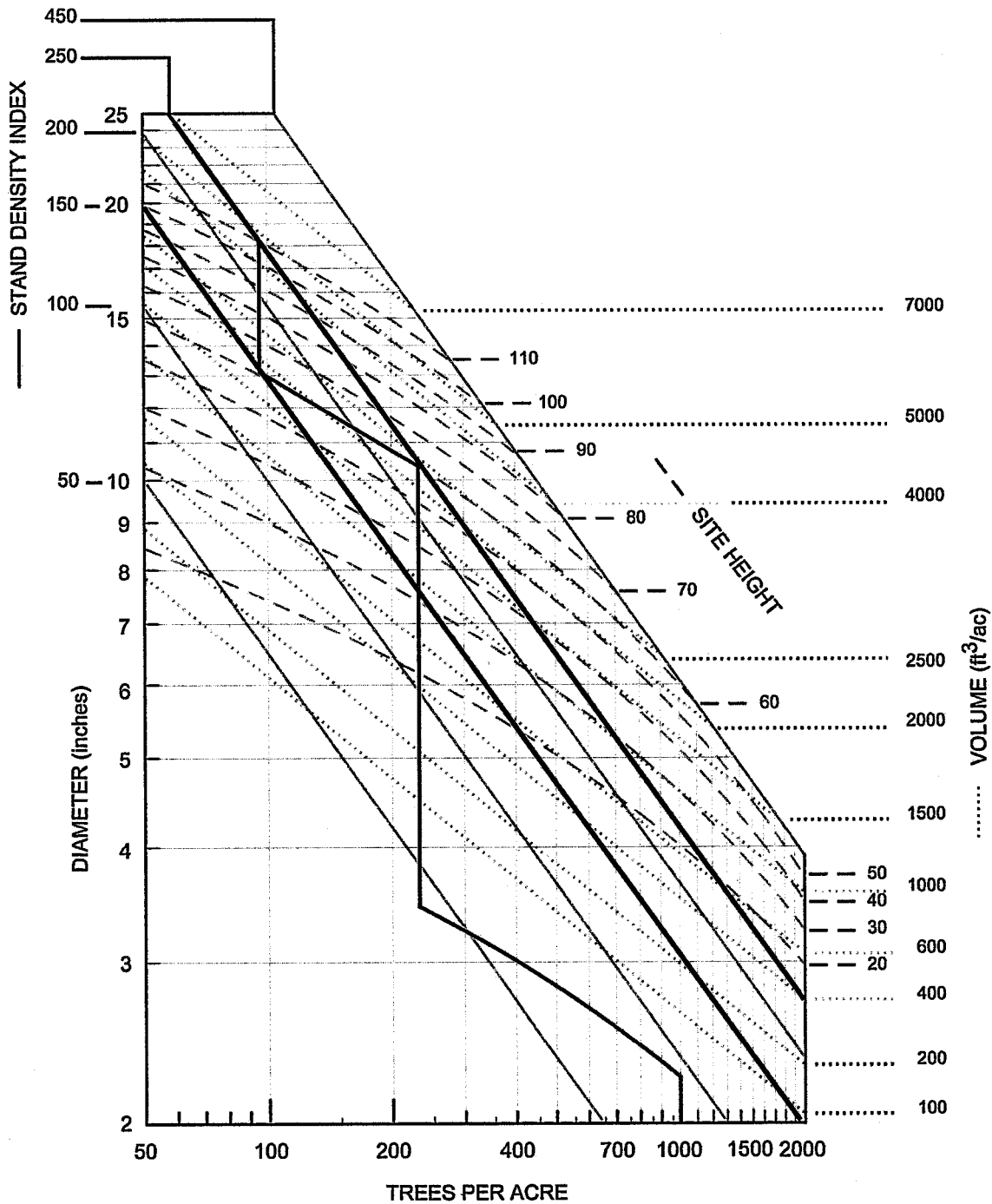


Figure 5. A density management regime with one precommercial and one commercial thinning.

Assessment and Use

Mountain Pine Beetle Attack

Increased susceptibility of ponderosa pine stands to attack by mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (MPB) is commonly associated with increased relative density. While the mechanism(s) responsible for this susceptibility-density relationship are not completely understood, there is considerable evidence for the effect (Negrón and Popp 2004). For example, Cochran et al. (1994) suggest for ponderosa pine stands in Oregon and Washington that SDI of 270 is a critical threshold for

when MPB mortality may become serious. They also suggest that the threshold SDI may be inversely proportional to site index.

For even-aged ponderosa pine stands in California, Oliver (1995) found a *Dendroctonus*-imposed upper limit of 365, independent of site quality. His data further suggest that endemic populations of beetles start to “thin” stands when their SDI reaches 230, which he characterizes as the beginning of the “zone of imminent bark beetle mortality.” Note that 365 and 230 are about 80% and 50%, respectively, of our SDI_{max} (i.e., 450).

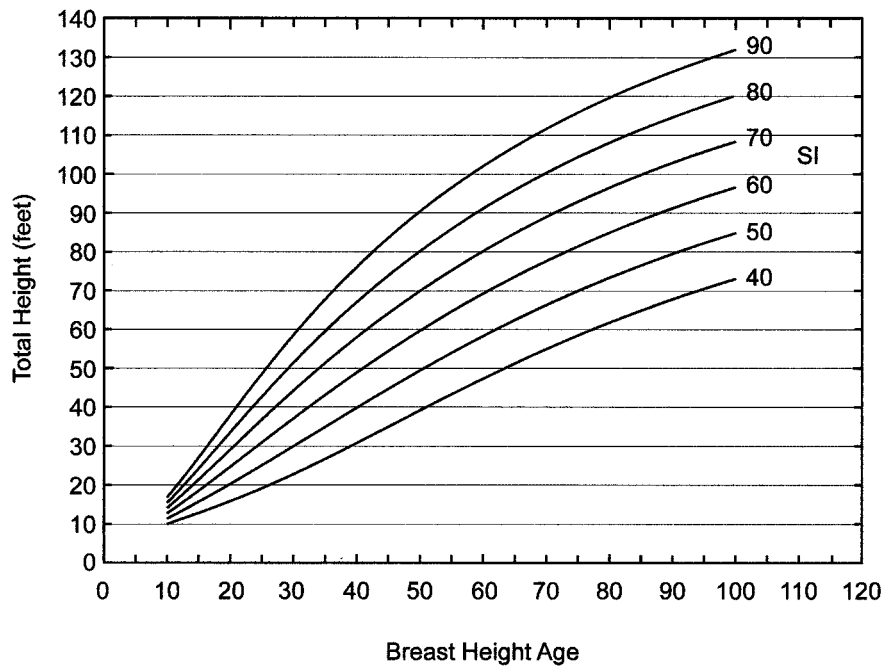


Figure 6. Height-age curves by site index (base 50) for ponderosa pine in western Montana (after Milner 1992).

Table 3. Site index curves and equations for ponderosa pine.

Reference	Coverage area
Barrett (1978)	Oregon and Washington
Brickell (1970)	Washington
Hann (1975)	Black Hills
Hann and Scrivani (1986)	Southwest Oregon
Lynch (1958)	Northern Idaho, Montana, and Washington
Meyer (1938)	California, Oregon, Washington, Idaho, Montana, and South Dakota
Milner (1992)	Western Montana
Minor (1964)	Northern Arizona
Powers and Oliver (1978)	California
Stansfield et al. (1991)	East-central Arizona
Summerfield (1980)	Eastern Washington

Designing a Density Management Regime and Incorporating Site Index

A key step in the design of a density management regime is deciding on appropriate upper and lower limits of relative density. What is appropriate, of course, will depend on the management objectives. In general, a density management regime that focuses on maximizing volume production will likely include a lower SDI of at least 150 (Table 2). Such a regime would likely include an upper SDI intended to minimize density-related mortality (e.g., 250 or $<60\%$ SDI_{max}). Conversely, a density management regime that focuses on rapid increases in tree size will likely include an upper SDI intended to minimize competition (e.g., 100 or $<25\%$ SDI_{max}).

A simple example illustrates the use of the DMD in developing and displaying a density management regime. For purposes of illustration, assume that a sapling stand has about 1,000 TPA and that the management objectives in

general mandate an end-of-rotation (EOR) Dq of 18 in. and maintenance of full site occupancy while minimizing density-related mortality. We will also assume that the regime may include a single precommercial thinning (PCT) and one or more commercial thinnings (CT) as long as the before-thinning Dq is >10 in. and that at least $500 \text{ ft}^3/\text{ac}$ are removed. Figure 5 displays an alternative density management regime that appears to meet the basic objectives. The first step was to draw upper and lower limits of 250 (“no self-thinning”) and 150 (“full site occupancy”), respectively. Then, working backward from the EOR ($Dq = 18$ and $SDI = 250$), the stand development trajectory is drawn. A line is dropped down to the desired lower limit, and then a thinning is simulated by extending a line across to the upper limit. The thinning line is drawn parallel to the height lines to simulate a thinning from below (e.g., there is an increase in Dq of about 2.5 in. because smaller than average diameter trees are removed, but top height remains constant). The volume removed in this thinning is about $600 \text{ ft}^3/\text{ac}$ (estimated from volume before thinning minus volume after thinning). This thinning, therefore, just meets the size and volume criteria assumed for a commercial thinning. It is obvious that this will be the only commercial thinning in the regime (given the chosen upper and lower limits and the minimum size and volume constraints).

To this point we have worked backward, but will now use a PCT to put the stand on a trajectory to the desired condition at the first commercial entry, i.e., the CT. Thus, after the PCT there should be about 225 TPA. Of course, the timing of the PCT could be influenced by any number of factors. For example, as illustrated (Figure 5), the PCT might be scheduled prior to substantial competition (e.g., $SDI < 100$) to delay self-pruning and thereby prolong the “window” of ungulate hiding cover (Smith and Long 1987)

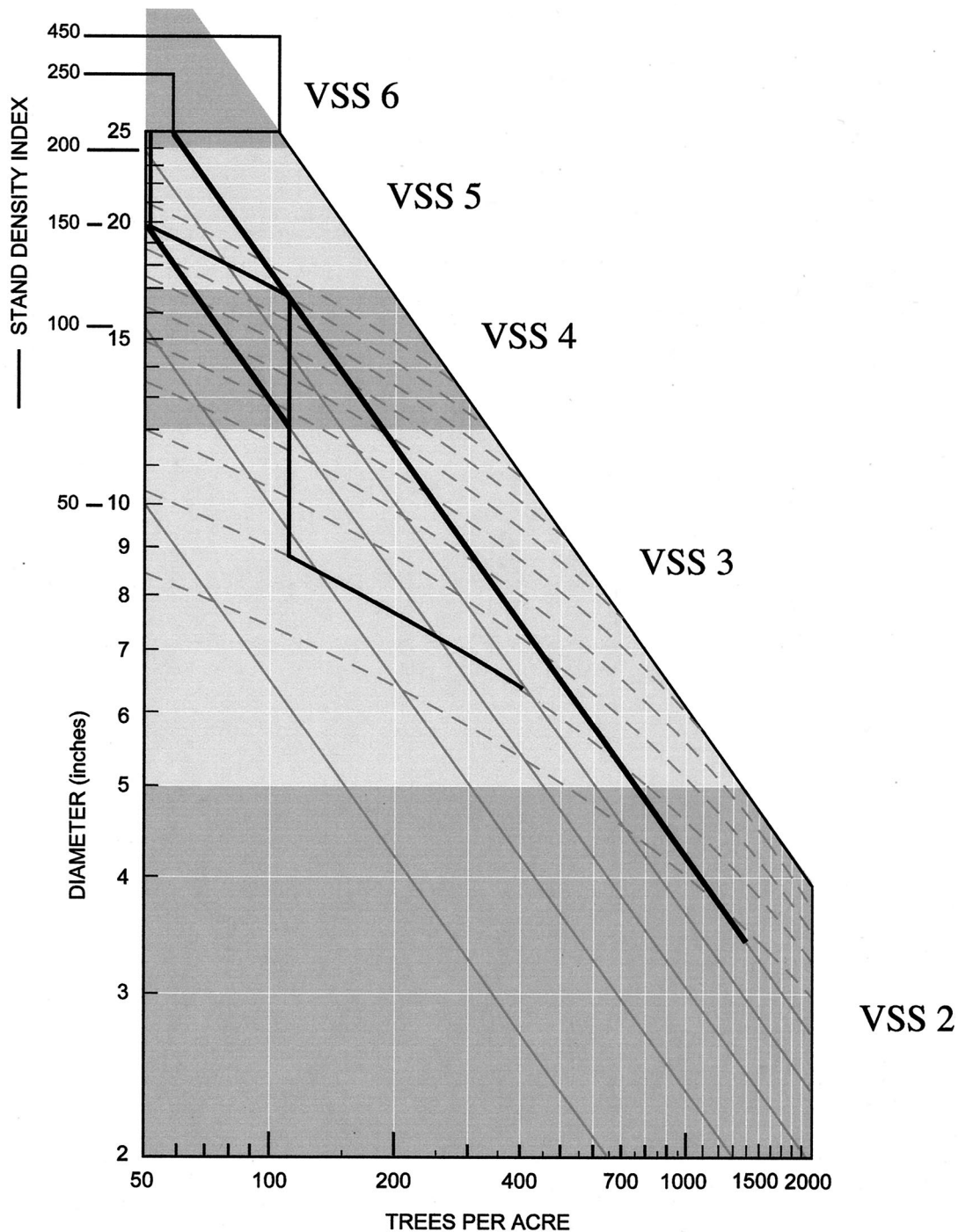


Figure 7. Density management related to vegetation structure stages (VSS). Ranges of diameters associated with the various VSSs are indicated by shading (e.g., VSS 3 from 5–12 in.).

or to prolong the “grass-forb-shrub” stage and maintain understory production (Long and Smith 1984). Alternatively, the PCT might be delayed until after the onset of competition (e.g., SDI > 100) to promote competition, self-pruning, and decreased knot sizes.

An appropriate site index curve allows the estimates of top height on the DMD to be a surrogate for time (Drew and Flewelling 1979). Using Milner’s (1992) curves for ponderosa pine in western Montana (Figure 6), and assuming for purposes of illustration, that site index is 80 ft (base age

50), the expected breast height age at commercial thinning is about 35 years, and the expected rotation breast height age is nearly 85 years.

Table 3 is a compilation of various published site index curves and equations for ponderosa pine from throughout its considerable geographic range in the United States.

Group Selection

The DMD was constructed with data from, and is intended for use in, essentially even-aged stands. We believe,

however, that the DMD has validity and considerable utility for exploring density management alternatives in the sorts of group selection systems contemplated under the Southwest goshawk guidelines (Reynolds et al. 1992, Long and Smith 2000). Where individual groups are large in a group selection system (e.g., >1 ac), it is appropriate to assess and manage relative density with approaches used in even-aged stand management rather than classic uneven-aged silviculture (e.g., see Guldin 1991 for an illustration of the *BDq* method).

The group is the regeneration unit of group selection systems, and therefore most trees in a group represent a single cohort and a single vegetation structural stage (VSS). Under the goshawk guidelines, it is intended that the distribution of trees within the group be nonuniform so that crowns of trees in mature groups interlock within clumps and are somewhat isolated from the crowns of trees in adjacent clumps (Reynolds et al. 1992). The average minimum canopy closure for the middle-aged, mature, and old groups (i.e., VSS 4–6) is 40%. An evaluation of Equation 3, assuming circular crowns and square spacing, suggests that for VSS 4–6, relative density should be maintained above SDI 140–150 to have at least 40% canopy closure.

It has been observed that currently in the Southwest there is no shortage of VSS 3 (i.e., average diameters from 5 to 12 in.), but there are deficits in the VSSs characterized by larger average diameters, particularly VSSs 5 and 6 (18–24 and 24+ in., respectively) (Long and Smith 2000). For even-aged stands or groups within a group selection system, Figure 7 illustrates a density management regime intended to put stands or groups currently in VSS 3 on an expeditious trajectory toward VSS 4. If the future desired condition is a *Dq* of 12 in. and SDI equal to 150, the DMD illustrates that the appropriate postthinning density is about 110 TPA (Figure 7). An alternative strategy might be to thin some VSS 3 so as to produce VSS 5 (i.e., *Dq* = 18 in. and SDI = 150) more quickly. Such a thinning would leave no more than 60 TPA. It would achieve VSS 5 characteristics sooner, but comprise the 40% canopy closure requirement for VSS 4. DMDs facilitate such a comparison of alternatives and is one of their important values.

Additional Considerations

We believe that the basic *Dq*, TPA, VOL, and HT40 relationships represented in the DMD are widely representative of even-aged ponderosa pine stands throughout its range in the United States. When using the DMD in a particular stand, users should be mindful of what the diagram represents. For example, the database used to construct the DMD was restricted to stands with at least 80% of their basal area contributed by ponderosa pine. Placement of maximum relative density lines is sensitive to the composition of mixed-species stands (Stout and Nyland 1986), and the proportion of species in a population will also influence the basic relations represented in a DMD. Therefore, pushing the DMD into mixed conifer stands, where ponderosa pine is not the dominant species, should be done with caution, if at all.

A similar caution relates to the SDI_{max} and other threshold values listed in Table 2. If a maximum size-density relation substantially less than 450 is deemed appropriate (e.g., based on extensive stand data for a particular plant association), then this insight should be incorporated into use of the DMD. For example, we suggest that 250 represents the approximate lower limit of the self-thinning zone (i.e., ~55–60% of SDI_{max}), and density management regimes should never be designed to exceed this threshold. If, however, it is assumed that the maximum size-density boundary is actually 350 instead of 450, then a reasonable estimate of the self-thinning threshold may be about 200.

Similarly, our interpretation of results from research relating MPB attack and relative density leads us to conclude that in general maintaining relative density below an SDI of about 250 should substantially reduce susceptibility to attack by MPB (and presumably other species of bark beetles). It is important to note, however, that results from some studies (e.g., Negron and Popp 2004) suggest that it may sometimes be prudent to adopt a lower relative density threshold, especially on poor sites. It is also worth noting that mean stand descriptors may not always provide meaningful characterizations of relative density (and susceptibility to MPB) for stands with a great deal of heterogeneity (Olsen et al. 1996).

Finally, we wish to emphasize that the DMD is not intended to replace the Forest Vegetation Simulator (FVS) (Wykoff et al. 1982, Johnson 1997), nor is it intended to replace silvicultural insight. Rather, the DMD is intended to complement both of these tools.

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