A Density Management Diagram for Even-Aged Sierra Nevada Mixed-Conifer Stands

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ABSTRACT

We have developed a density management diagram (DMD) for even-aged mixed-conifer stands in the Sierra Nevada Mountains using forest inventory and analysis (FIA) data. Analysis plots were drawn from FIA plots in California, southern Oregon, and western Nevada which included those conifer species associated with the mixed-conifer forest type. A total of 204 plots met the selection criteria for analysis, which were for even-agedness and species composition. Even-agedness was characterized by a ratio between two calculations of stand density index. Species composition included admixtures of the species characterizing the Sierra Nevada mixed-conifer type with up to 80% of stand basal area contributed by ponderosa and Jeffrey pines. The DMD is unbiased with respect to species composition and therefore should be broadly applicable to the mixed-conifer type. 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.

Keywords: silviculture, maximum stand density index, stocking diagram, mixed species

Density management diagrams (DMD) are simple graphical models of even-aged stand dynamics. A DMD is based on fundamental assumptions about the influence of density on important stand properties and processes including allometries, competition, site occupancy, and self-thinning (Jack and Long 1996, Newton 1997, Farnden 2002). Details of formatting vary, but all of the DMDs include representation of absolute density (e.g., trees per acre), relative density, volume (stand or mean tree) and quadratic mean diameter. In contrast to stocking charts, DMDs include the important feature of representation of top heights so that when paired with appropriate site or top height growth curves, DMDs can be used to project future growth (Drew and Flewelling 1979, McCarter and Long 1986, Jack and Long 1996).

DMDs are useful tools in developing, evaluating and displaying alternative density management regimes for objectives ranging from increasing resistance to bark beetle attack and protection forest function, to maintaining habitat for birds, ungulates and forest carnivores (Smith and Long 1987, Anhold et al. 1996, Sturtevant et al. 1998, Long and Shaw 2005, Shaw and Long 2007, Whitehead et al. 2007, Vacchiano et al. 2008). A number of DMDs have been published for species in western Canada and the western United States (Table 1).

In addition to conforming to some approximation of even-agedness, conventional DMDs are built with data from, and are intended to be used with, essentially single-species stands. For example, a ponderosa pine DMD (Long and Shaw 2005) is intended for use with stands in which ponderosa pine represents at least 80% of total stand basal area. For many management situations, the single-species restriction is not a serious limitation; however, there are several forest cover types in the western United States that are explicitly mixed-species (Eyre 1980). An important example is the Sierra Nevada mixed-conifer type (Helms 1994). Species composition of the type has been variously characterized, but stands typically include California white fir (*Abies concolor* var. *lowiana* (Gord.) Lemm.), ponderosa pine (*Pinus ponderosa* var. *ponderosa* Dougl.), sugar pine (*Pinus lambertiana* Dougl., incense-cedar (*Calocedrus decurrens* (Torr.) Florin), California black oak (*Quercus kelloggii* Newb.), and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Eyre 1980). Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) can be an important component of stands at higher elevations and particularly on serpentine soils (Helms 1994). California red fir (*Abies magnifica* A. Murr.) can occur in stands at higher elevations (Eyre 1980). The Sierra Nevada mixed-conifer type, common at mid-elevations on east-facing slopes of the Coast Ranges and west-facing slopes in the Sierra Nevada, is the forest type in California with the largest area (Helms 1994).

We describe the construction of a DMD for even-aged mixed-conifer stands in California, southern Oregon, and western Nevada. We examine whether differences in species composition within the broad mixed-conifer type might impact utility of the DMD. Use of the DMD is illustrated with several management examples.

Development

Database

Because forests of the mixed-conifer type are compositionally and geographically diverse, we obtained data available in the US forest service forest inventory and analysis (FIA) surveys completed in Washington, Oregon, California and Nevada between 1989 and 2009 ($n = 9917$). The FIA program defined a California mixed-conifer type (Arner et al. 2001), but we did not use this forest type as a selection criterion because it is restricted to a few counties in

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Table 1. Density management diagrams for western North America species. Each DMD displays relationships between volume (total or mean), quadratic mean diameter, absolute density (e.g., TPA), relative density (e.g., SDI), and top height.

Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco)	Drew and Flewelling (1979), Long et al. (1988), Farnden (1996)
Lodgepole pine	*Pinus contorta* Dougl. var. *latifolia* Engelm.	McCarter and Long (1986), Farden (1996)
Ponderosa pine	*Pinus ponderosa* Laws.	Long and Shaw (2005)
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.	Flewelling et al. (1980)
Western redcedar	*Thuja plicata* Donn ex D. Don	Smith (1989)
White spruce	*Picea glauca* (Moench) Voss	Farnden (1996)

California and thus too restrictive for the purposes of diagram construction and field application. Instead, we selected plots that included combinations of the species characteristic of the Sierran mixed-conifer types (Franklin and Halpern 2000, Barbour and Minnich 2000): California red fir, white fir, Douglas-fir, ponderosa pine, Jeffrey pine, sugar pine, incense-cedar, and California black oak.

The FIA database included separate tables for trees, plots, and conditions. FIA plots can sample one or more conditions, where each condition was identified as a relatively homogeneous portion of a plot based on stand size class, composition, or other criteria—i.e., an FIA condition was approximately equivalent to a stand. Variables such as forest type, stand size class, and productivity class were assigned to the condition and not the plot. Condition proportion was recorded for each condition, based on the fraction of the plot footprint occupied. Plot-level data included mostly site characteristics, such as latitude, longitude, slope, aspect, elevation, and ecoregion. For each tree ≥ 1.0 in dbh we obtained the following variables from the FIA database: state, county, plot number, species, diameter, height, trees per acre (expansion factor), and individual tree cubic-foot volume. FIA data included volume on a per tree basis 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 each species represented in the stand, and computed basal area percentage of each of the species indicative of the forest type. Stand top height was defined as the mean height of the 40 tallest trees per acre found on each subplot in the FIA plot (HTAvg). This method of estimating stand top height gave comparable results to more complicated approaches—e.g., determining the mean height of the 40 tallest trees acre—and eliminated the possibility that stand top height could be heavily influenced by a clump of tall trees on a single subplot. Stand density index (SDI; Reineke 1933) was calculated using the quadratic mean diameter and summation methods (SDI_{Dq} in Equation (1) and SDI_{sum} in Equation (2)).

$$SDI_{Dq} = \left(\frac{D_q}{10}\right)^{1.6} \cdot TPA \qquad (1)$$

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

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

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 2009, Curtis 2010). 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 approached 1 for stands that were 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. SDI ratio fell below 0.94 for stands with bimodal diameter distributions, with lower values found in stands where the modes were more widely separated. For example, a stand with a

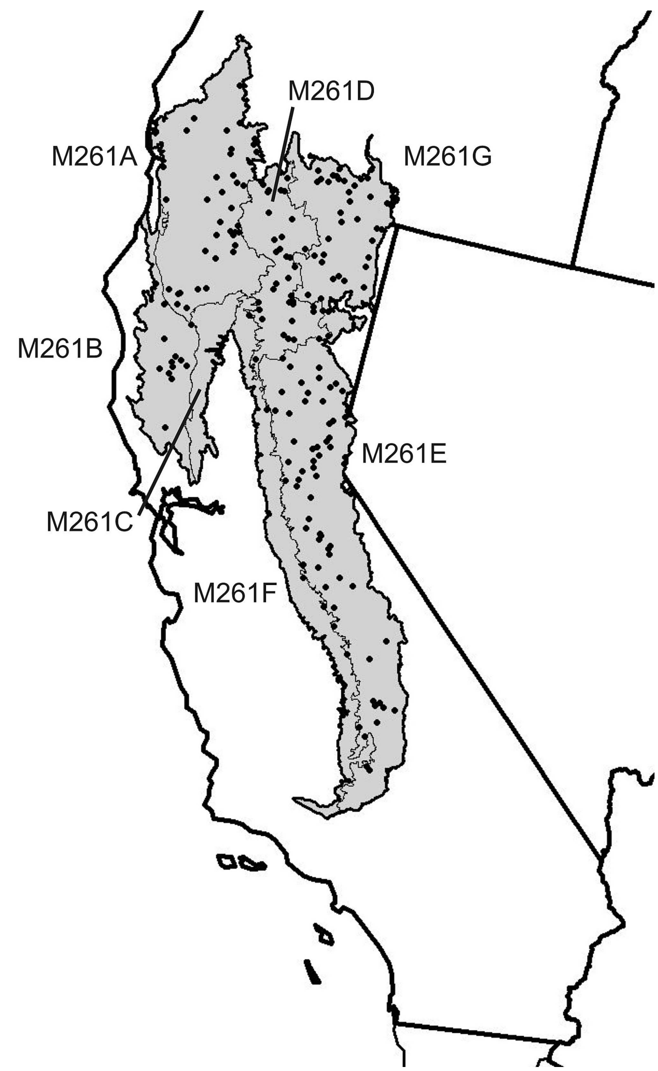

Figure 1. Location of plots used to develop the density management diagram. Shaded area is the Sierran Steppe – Mixed Forest – Coniferous Forest – Alpine Meadow Province (Bailey 1996). Ecoregion section codes, based on Cleland et al. (2005): M261A-Klamath Mountains Section, M261B-Northern California Coast Ranges Section, M261C-Northern California Interior Coast Ranges Section, M261D-Southern Cascades Section, M261E-Sierra Nevada Section, M261F-Sierra Nevada Foothills Section, M261G-Modoc Plateau Section.

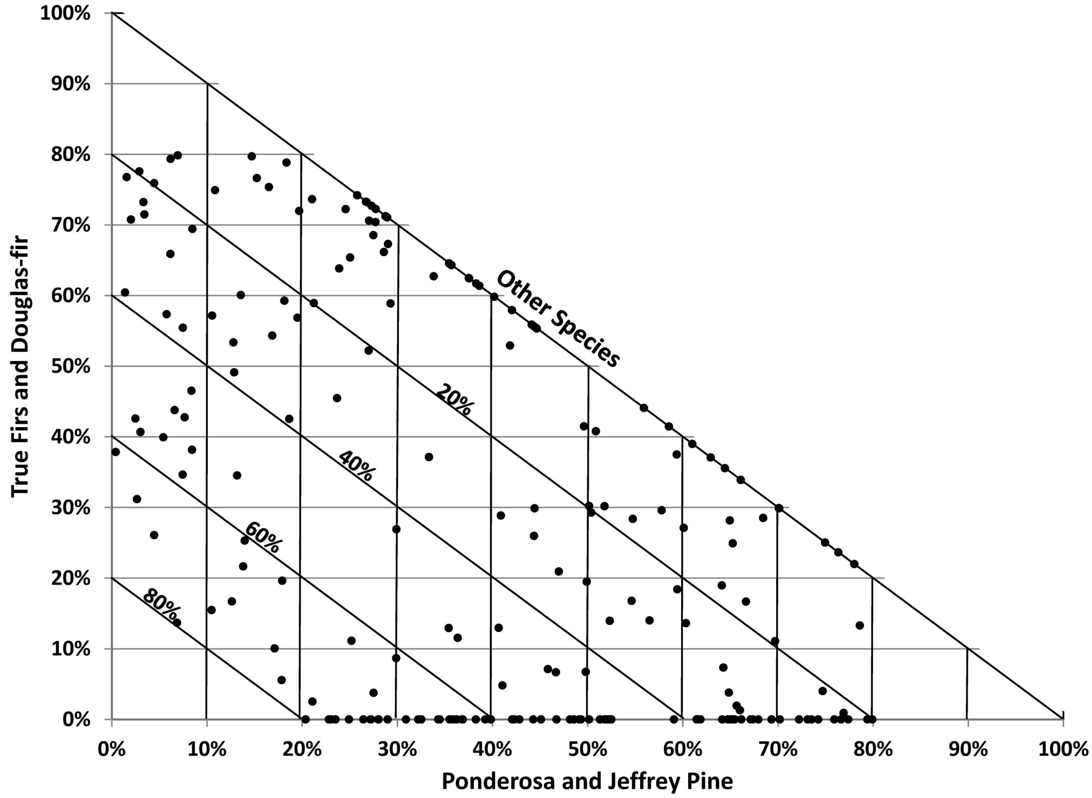

Figure 2. Composition by species group for plots used to develop the density management diagram.

large-tree component averaging 22 inches and a small-tree component averaging 5 inches would have an SDI ratio of about 0.86 (Ducey 2009).

Because some of the characteristic species have broad ranges and form mixtures outside our compositional range of interest (e.g., Douglas-fir-dominant mixtures that do not include others of the characteristic species noted above), we initially filtered plots in the four-state area according to the following criteria: the presence of either ponderosa or Jeffrey pine with any of the other species noted above. As a result of selecting plots based on composition rather than strict geographic boundaries, the California mixed-conifer type was found to occur over a broader area than the name implies—approximately coinciding with the extent of the Sierran Steppe – Mixed Forest – Coniferous Forest – Alpine Meadow Province described by Bailey (1996) and most recently revised by Cleland et al. (2005) (Figure 1). Only plots from this province were considered for further analysis.

The data were filtered to eliminate plots with: (1) fewer than 25 trees per acre because relatively few (<5) trees were measured on these plots, (2) a condition proportion < 0.75, to eliminate small sampling areas, (3) quadratic mean diameters < 2.0 inches, and (4) the ratio of SDI_{sum}:SDI_{Dq} < 0.94. Using a minimum condition proportion of 0.75 ensured that only one condition could be used from each plot, so the term "plot" will be used hereafter, even when it does not refer to the entire FIA plot. The selection of 0.94 as a cutoff for SDI ratio represented an approach for retaining even-aged of stands in the sample. It is noteworthy that this cutoff also resulted in the elimination of stratified mixtures, even those that were even-aged. There was no filtering with respect to previous disturbances.

The data were further filtered to eliminate plots from three species groups: greater than 80% basal area contributed by ponderosa and Jeffrey pines combined; greater than 80% basal area of true firs and Douglas-fir combined; and greater than 80% basal area of other species combined (Figure 2). Our reasoning for these compositional limits was as follows: the requirement for some amount of ponderosa or Jeffrey pine is definitional; and the DMD is intended for mixed stands that are at least capable of having a ponderosa or Jeffrey pine component. The upper limit for each of the species groups was based on the logic that 80% represents a "pure" condition, and that stands in this compositional range would warrant the development of separate DMDs, e.g., as done for ponderosa pine (Long and Shaw 2005).

The plots selected for analysis covered a wide range of composition. Even-aged stands with approximately equal representation of all three species groups were not very common, and stands with two of the three groups present (i.e., ponderosa pine-Jeffrey pine / true fir-Douglas-fir or ponderosa pine-Jeffrey pine / incense-cedar-sugar pine-California black oak) were somewhat common (Figure 2). Plots were well-distributed within the Sierran Steppe – Mixed Forest – Coniferous Forest – Alpine Meadow Province, with the exception of the Northern California Interior Coast Ranges Section, where no suitable plots were found (Figure 1). Elevations of sample plots followed a strong gradient with changing latitude; northern California stands are generally located between 1300 and 6200 ft, while central and southernmost stands are located between 3000 and 7900 ft. The final number of plots retained for analysis was 204.

Construction of the Diagram

The density management diagram (Figure 3) were formatted in the style introduced by McCarter and Long (1986), with Dq and TPA on the major axes and relative density represented by SDI up to

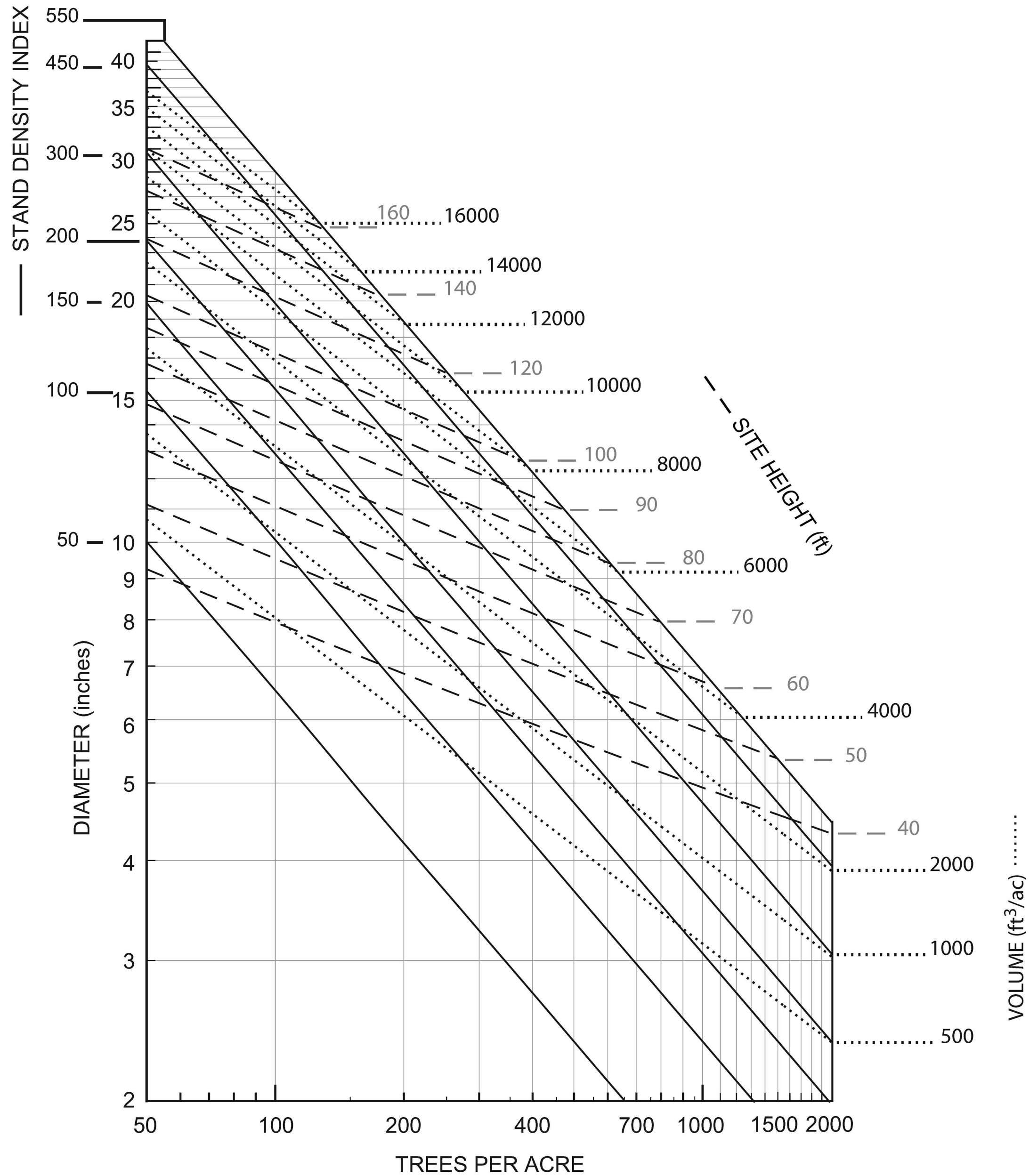

Figure 3. A density management diagram for even-aged Sierra Nevada mixed-conifer stands. The stand volume and top height isolines were generated from the regression models in Table 3.

a maximum of 550. The DMD also included lines representing estimates of stand volume (ft^3/ac) and site or top height (ft).

SDI_{max} is an approximation of the maximum size-density relation—the theoretical boundary for combinations of mean diameter and density. It is important to be clear concerning the SDI_{max} construct. SDI_{max} represents an empirically based estimate of the maximum combination of quadratic mean diameter and density which can exist for any stand of a particular forest type. In a large sample of stands, the vast majority will have combinations of mean size and density below the estimated maximum. In such a large sample, only a few stands will have SDI values close to the putative $SDI_{max.}$ and stands with SDIs greater than SDI_{max} will be vanishingly rare. Confusion can arise when alternative characterizations of 'maximum SDI' are used without explicit explanation. 'Average maximum density' (AMD) is, for example, an alternative characterization corresponding to the average SDI of self-thinning stands; AMD is assumed to be about 80% of SDI_{max} (Long and Shaw 2005).

The SDI_{max} for a mixed-species stand is, of course, a function of the proportions of species in the mixture and their individual maxima. The maximum SDI represented on the diagram is 550. We arrived at this maximum using a distribution-based method, where the maximum for a defined forest type is based on a fixed percentile of plots meeting the type definition. Figure 4 shows the distribution of SDI for conditions meeting our compositional criteria, before filtering for stand structure (SDI ratio) and condition proportion. Reineke (1933) indicated a maximum of approximately 750 for "mixed conifer stands in California." However, Reineke's method of determining maximum SDI for this and other forest types was somewhat subjective (ruler-pencil). His estimate of 830 for ponderosa pine greatly exceeded more recent figures for the species

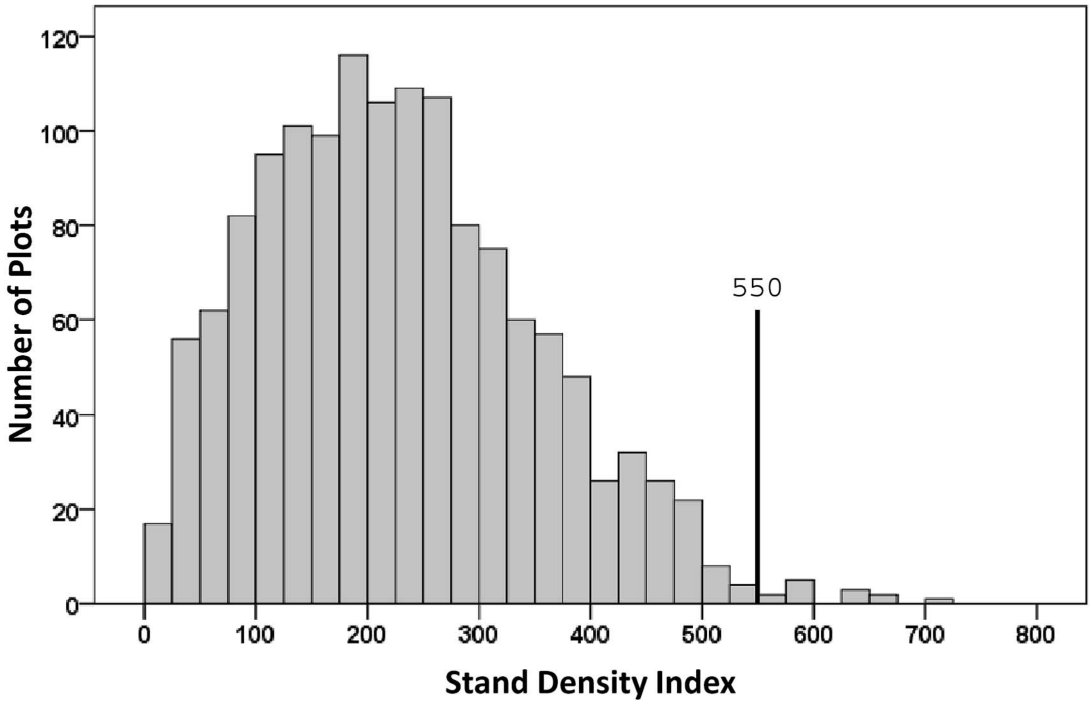

Figure 4. Distribution of SDI for FIA plots in the Sierran Steppe – Mixed Forest – Coniferous Forest – Alpine Meadow Province meeting the compositional criteria for the Sierra Nevada mixed-conifer forest type. Bar indicates the SDI_{max} set in the density management diagram.

Table 2. Typical composition of mixed-conifer types reported by Dunning and Reineke 1933.

	Species (SDImax)						
Type	PP (446)	SP (561)	DF (570)	WF (634)	IC (576)	RF (768)	SDImax
PP-fir	40	3	30	20	7	0	533
PP-SP	40	37	3	10	10	0	524
PP-SP-fir	40	25	10	20	5	0	531
SP-fir	5	33	20	35	7	0	584
WF-DF	5	3	45	45	2	0	592
WF-RF	0	3	0	68	0	29	671

Cell values are average percentages of each species (column) in each named forest type (row). Values in parentheses are SDImax values assigned to each species in our analysis. SDImax for each forest type is our weighted SDImax, based on the proportion of each species in the type. PP, ponderosa pine; SP, sugar pine; DF, Douglas-fir; WF, white fir; IC, incense-cedar; RF, red fir.

(Long and Shaw 2005, Shaw and Long 2010). In addition, Reineke (1933) did not provide the species composition of his mixed-conifer stands. It is likely that the data he used to show SDI for "mixed conifers in California" were the same as reported by Dunning and Reineke (1933)—311 plots with varying mixtures of the defining species. Dunning and Reineke (1933) provided a summary table of forest types represented in their data, with mean percentages of the type-defining species. When we applied our distribution-based maximum to each of the species in the mixed types, the SDI_{max} values we obtained are consistent with the maximum used in our DMD (Table 2). We note that the forest types with the two highest SDI_{max} values in the table, white fir / Douglas-fir (592) and white fir / red fir (671) would be excluded from our analysis because they exceeded 80% basal area limit for the true fir-Douglas fir species group.

The stand volume and site or top height isolines on the DMD (Figure 3) were developed from nonlinear regressions relating either VOL or HTAvg to Dq and TPA (Table 3). Both regression models accounted for much of the variation in the data and were essentially unbiased with respect to the predictor variables, as well as site index, SDI, volume, basal area and species composition represented by percentage of ponderosa pine basal area. The models somewhat overestimate HTAvg and VOL, respectively, at higher elevations (e.g., > 7000 ft) and lower site indexes (e.g., < 50 ft base age 50).

Table 3. Regression models used to generate volume and height isolines.

	a	b	c	d	adjusted R^2	MSE
$HTAvg = ((a + QMD)/(b * TPA^c))^d$						
Estimate	−1.143	0.679	−0.254	1.062	0.97	±1.02 ft
S.E.	0.964	0.237	0.020	0.084		
$VOL = a * TPA^b * QMD^c$						
Estimate	0.007	1.146	2.808		0.96	$\pm 42\ ft^3\ ac^{-1}$
S.E.	0.002	0.030	0.053			

Based on analysis of residuals, the basic relationships (i.e., stand volume and top height corresponding to a given Dq and TPA) captured in the diagram appeared to be independent of both site quality and species composition. The ranges of the Dq and TPA axes and the HTAvg and VOL lines were chosen to approximate the range of values represented by the 204 stands in our data set.

Assessment and Use

Designing a Density Management Regime and Incorporating Site Index

DMDs are useful tools for the initial development and comparison of density management alternatives. A key step in the design of a density management regime is deciding on appropriate upper and lower limits of relative density. These choices are strictly situational

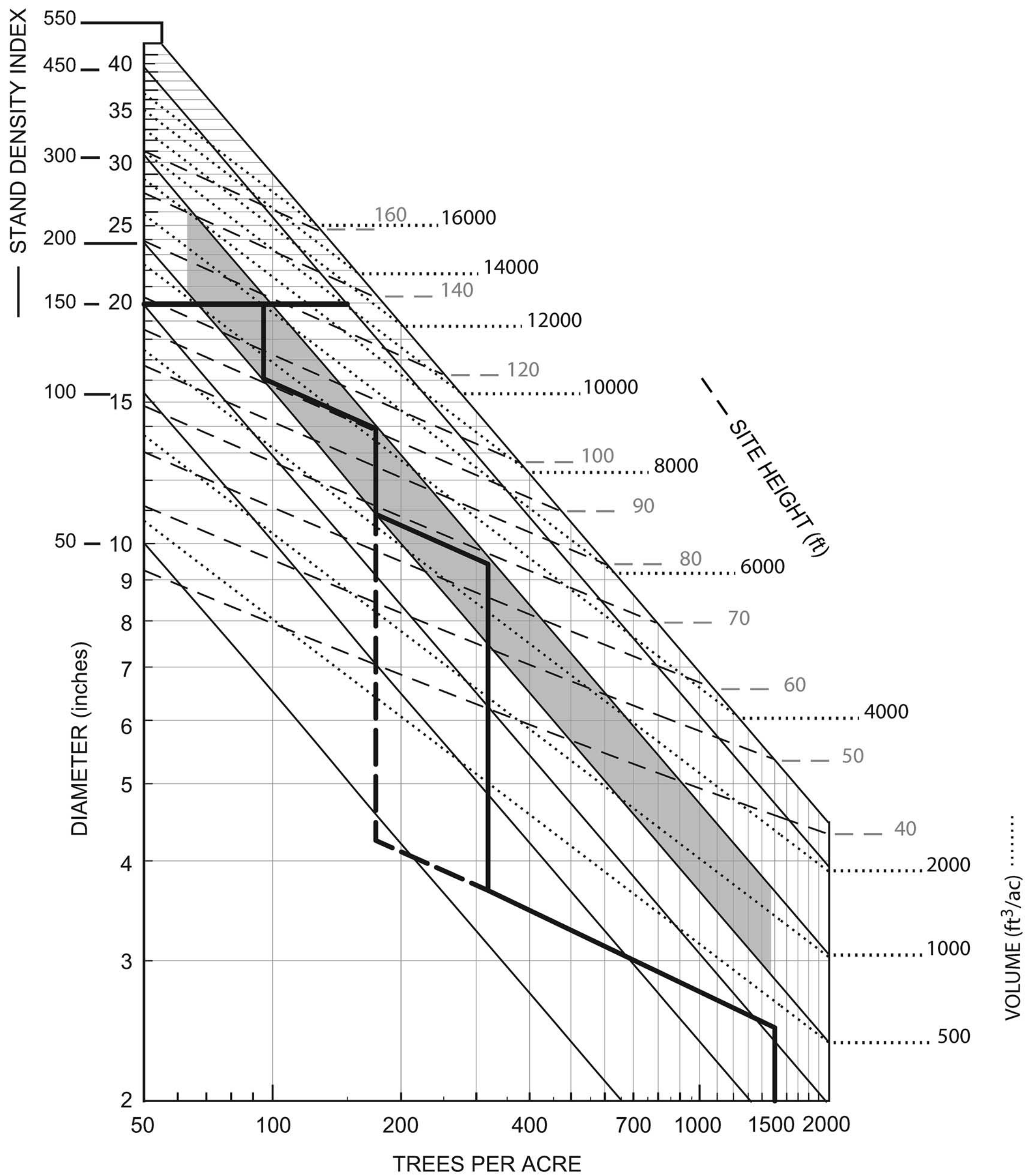

Figure 5. Density management regimes with one precommercial and one or two commercial thinnings. The shaded area includes a range of SDI representing reasonably full site occupancy and the avoidance of substantial self-thinning.

and must be made in the context of stand-specific management objectives (Long 1985). For example, an objective to avoid substantial density-related mortality (self-thinning) would imply an upper limit less than ~ 60% SDI_{max}, and avoiding what Drew and Flewelling (1979) characterized as the zone of imminent competition-mortality. A lower limit of at least 35% of SDI_{max} would ensure full site occupancy and might be associated with an objective involving maximizing volume production.

We provide a simple, hypothetical example to illustrate use of the Sierra Nevada mixed-conifer DMD and to motivate further consideration of SDI_{max}. In this example, we are exploring alternative density management regimes for a naturally regenerated mixed-conifer stand which currently has about 1500 saplings per acre. We are considering an immediate precommercial thinning (PCT), but, of course, we wish to consider long- as well as short-term alternatives. For this hypothetical stand our general management objectives include avoiding substantial self-thinning, maintaining reasonably full site occupancy and an end-of-rotation (EOR) Dq of 20 inches. We also assume we have the option of considering commercial thinning (CT) as long as the before-thinning Dq is at least 10 inches and at least 1000 ft^3/ac are removed.

Figure 5 displays alternative density management regimes consistent with the basic objectives. The first step was to draw an upper SDI limit of 300 (<60% of SDI_{max}, i.e., no substantial self-thinning) and a lower limit of 200 (~35% of SDI_{max}, i.e., reasonably full site occupancy). Then, working backwards from the EOR (Dq = 20 and SDI = 300), a line is dropped down to the desired lower limit and then a thinning is represented by extending a line across to the upper limit. The thinning line is drawn parallel to the height lines (in this specific case corresponding to a top height of about 90 ft). Drawing the thinning in this way simulates a low thinning in which Dq increases (from about 14 inches to 16 inches)

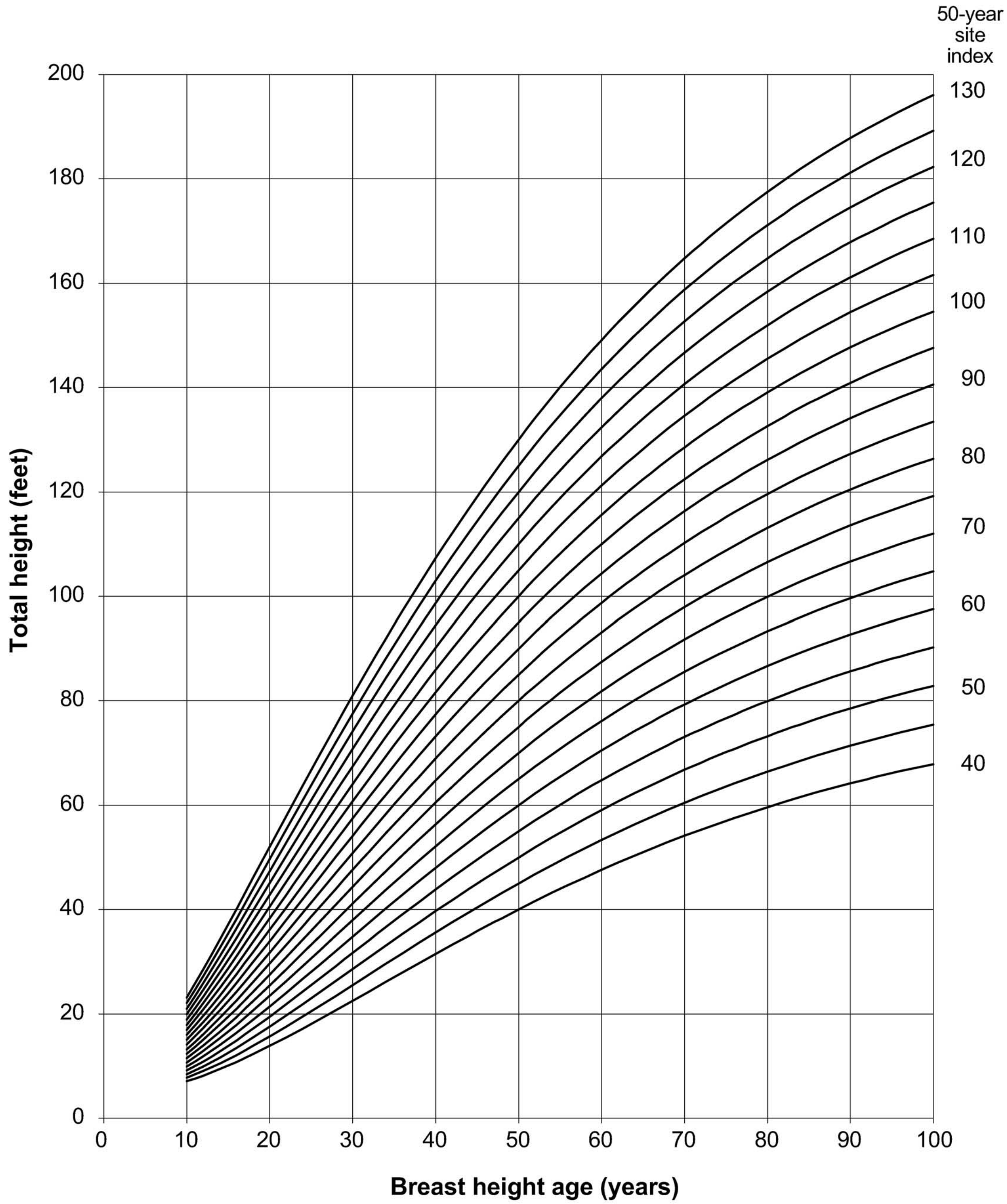

Figure 6. Height-age curves by site index (base 50) for young Sierra Nevada mixed-conifer stands (after Biging and Wensel 1985).

as a result of removing nearly 80, generally smaller than average, trees per acre. A basic assumption is that these relationships are independent of site quality and changes following thinning are fairly minor and short-lived (Jack and Long 1996). The estimated volume removed, about 1000 ft^3/ac, is the difference between volume before and volume after thinning. Therefore, both the size and volume criteria for a CT appear to be met.

Continuing in this way results in the display of another potential CT. The estimated volume removed (~800 ft^3/ac) and the small piece size may make this CT problematic. We could use the PCT to reduce stand density to about 310 TPA so as to setup this first of two putative CTs. A more attractive alternative is to forego the marginal CT and use the PCT to reduce stand density to about 170 TPA so as to setup a CT when Dq is about 14 inches. A potential advantage of the two CT alternative is a modest increase in yield (i.e., 800 ft^3/ac removed in the first CT). A very serious potential disadvantage of this alternative is that when the stand achieves a Dq of 9.5 inches, this putative first CT may not be economically viable. The small volume to be removed and the small piece size might make harvest and handling costs prohibitive. Absent the option of a CT, the silviculturist would be left with two equally undesirable choices for the stand—conduct a second PCT or allow the stand to self-thin its way to a mean size sufficient to justify a CT.

Once density management regimes have been displayed on the DMD, an appropriate site index curve allows the estimates of top height to be a surrogate for time (Drew and Flewelling 1979). Using the Biging and Wensel (1985) site index curves for young-growth mixed-conifer stands (Figure 6), and assuming for illustration, that site index is 100 ft (base age 50), the expected rotation breast height (BH) age is about 60–65 years. Similarly, the CT associated with a top height of about 90 ft (Figure 5), would correspond to a BH age of about 45 years (Figure 6).

Additional Considerations

The proceeding example illustrates the importance of SDI_{max} in the design of realistic density management regimes. At the beginning of the process, stand management objectives are qualitative, e.g., "maintain relative densities so as to fully occupy the site but avoid substantial self-thinning." Eventually, the silviculturist must be able to explicitly quantify each entry in the proposed density management regime, e.g., "when Dq = 14 inches, thin from below to a residual density of 100 TPA." Practically speaking, making the leap from conceptualizations of stand dynamics to details of density management requires a realistic characterization of relative density. SDI as a percentage of maximum SDI is such a characterization of relative density. The appropriate use of this metric presupposes that SDI_{max} has been correctly identified.

The DMD (Figure 3) was constructed with data from, and is intended to be used with, stands with a mixture of conifer species representative of the Sierra Nevada mixed-conifer type. Within this considerable variation in species composition (e.g., Figure 2), the DMD appears to provide reasonable approximations of size-density relationships and stand dynamics. It is important to emphasize that the representation of SDI_{max} as 550 is an approximation for mixtures including species which, if in pure stands, should have a much higher SDI_{max} as well as species with a much lower SDI_{max}. For specific mixtures, SDI_{max} can be estimated by using the species-specific SDI_{max} values at the top of Table 2 (SDI_{max} values for Jeffrey pine and California black oak, not given in Table 2, are 497 and 406, respectively) and weighting the values by basal area percentage as done in the table. The DMD should not be used in stands whose composition falls outside the ranges used in selecting stands used in construction of the diagram. Specifically, the DMD should not be used for stands with greater than 80% basal area contributed by ponderosa and Jeffrey pines combined, greater than 80% basal area of true firs and Douglas-fir combined, and greater than 80% basal area of other species combined (Figure 2). For stands dominated (i.e., > 80% of stand BA) by ponderosa pine we recommend using a different DMD (Long and Shaw 2005). Use of the DMD should also be restricted to stands which are not strongly stratified.

The example density management regimes (Figure 5) are based on the expectation that 550 will remain a reasonable approximation of SDI_{max} over the entire rotation. In other words, it is assumed that the planned thinnings (the PCT and either one or two CTs) will not alter species composition to the extent that the stand would be dominated by either a high SDI_{max} species (e.g., California white fir) or a low SDI_{max} species (e.g., ponderosa pine). Alternatively, for example, if the intent is to use the PCT to shift species composition toward ponderosa pine (as might happen, for example, if the objective were to favor more fire resistant trees), the choice of SDI_{max} should be reconsidered and details of the density management regime changed accordingly. For the objective to avoid substantial self-thinning, an appropriate upper SDI would be 250 (< 60% of 450) rather than 300 (< 60% of 550).

The DMD was constructed with data from, and is intended for use in, essentially even-aged, unstratified stands. In a group selection system when the individual groups are large (e.g., > 1 acre), it is appropriate to assess and manage relative density with approaches used in even-aged stand management rather than classic uneven-aged silviculture (Long and Smith 2000). For this reason we believe the Sierra Nevada mixed-conifer DMD has utility for exploring density management alternatives in large group selection systems.

Finally, as with any DMD, the Sierra Nevada mixed-conifer DMD is not a replacement for the forest vegetation simulator (FVS) (Wykoff et al. 1982, Johnson 1997). We argue that its most appropriate application will be the initial assessment of density management alternatives and the effective communication of silvicultural insight.

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