A Density Management Diagram for Longleaf Pine Stands with Application to Red-Cockaded Woodpecker Habitat

John D. Shaw and James N. Long

ABSTRACT

We developed a density management diagram (DMD) for longleaf pine (*Pinus palustris* P. Mill.) using data from Forest Inventory and Analysis plots. Selection criteria were for purity, defined as longleaf pine basal area (BA) that is 90% or more of plot BA, and even-agedness, as defined by a ratio between two calculations of stand density index. The diagram predicts stand top height (mean of tallest 40 trees/ac) and volume (ft^3/ac) as a function of quadratic mean diameter and stem density (trees/ac). In this DMD we introduce a "mature stand boundary" that, as a model of stand dynamics, restricts the size–density relationship in large-diameter stands more than the expected self-thinning trajectory. The DMD is unbiased by geographic area and therefore should be applicable throughout the range of longleaf 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. Use of the diagram is illustrated by development of density management regimes intended to create and maintain stand structure desirable for the endangered red-cockaded woodpecker (*Picoides borealis*).

Keywords: *Pinus palustris*, *Picoides borealis*, silviculture, stand density index, stocking diagram

Density management diagrams (DMD) are simple graphical models of even-aged stand dynamics. They reflect fundamental relationships involving size, density, competition, site occupancy, and self-thinning (Jack and Long 1996). DMDs are used to determine what postthinning density will result in the type of stand desired at the next entry (Farnden 2002). They also are extremely useful in displaying and evaluating alternative density management regimes intended to accomplish diverse objectives (Long and Shaw 2005). DMDs exist for a number of species in Canada and the northeastern and western United States (e.g., Wilson et al. [1999], Farnden [2002], and Long and Shaw [2005]).

For the southern United States, DMDs have been constructed for loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.; Dean and Jokela [1992], Dean and Baldwin [1993], and Williams [1994]), but none have been developed for longleaf pine (*Pinus palustris* P. Mill.). Increasing interest in restoration and management of longleaf pine forests has created a need for management tools such as growth models and DMDs. Here, we describe the construction of a DMD for even-aged longleaf pine and illustrate its use with examples based on management for red-cockaded woodpecker (RCW; *Picoides borealis*) habitat.

We included the RCW example because of the important link between recovery of the RCW population and restoration of longleaf pine across their common range. With respect to managing stands to produce good RCW foraging habitat, we have attempted to reconcile the structural criteria given in the RCW recovery guidelines (US Fish and Wildlife Service 2003) with a broad-based understanding of stand dynamics in the pure (or nearly so) longleaf forest type.

Methods

Data Development

Data used for construction of the DMD were drawn from USDA Forest Service Forest Inventory and Analysis (FIA) surveys completed between 1984 and 2003 in all states that included some part of the native range of longleaf pine (Little 1971). Survey data were obtained from the FIA database (FIADB) website (Miles et al. 2001, USDA Forest Service 2005). Under the current FIA design, plots may be mapped into more than one condition based on, e.g., stand size class or stem density (Conkling and Byers 1993). We obtained a total of 5,222 conditions with at least 1 longleaf pine present as potential study plots (Figure 1; Table 1). The term "plot" will be used hereafter as a synonym for the FIA condition.

We obtained the following variables from the FIADB (Miles et al. 2001) for trees 1.0-in. dbh or more: species, diameter, height, trees per acre (TPA; expansion factor), and individual net cubic-foot volume (trees 5.0 in. dbh or more, from a 1-ft stump to a minimum 4-in. top diameter outside bark). Because of changes in FIA survey design over the years, measured heights were not available for all trees in the database. Therefore, we estimated height using an equation developed from all available height data in the FIADB (Equation 1):

$$\log_{10}\mathrm{HT} = 0.839 + (0.975\log_{10}\mathrm{dbh}^{0.615})$$

$$- 0.0000305\ \mathrm{TPA}(n = 1{,}386;\ R^2 = 0.85) \quad (1)$$

where HT is total tree height, dbh is diameter at breast height, and TPA, as mentioned previously, is number of trees per acre.

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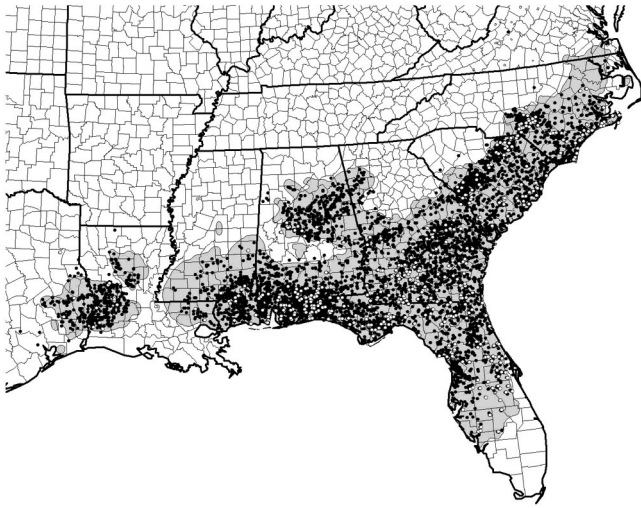
Figure 1. Range of longleaf pine (Little 1971) and locations of FIA plots with at least one longleaf pine present (solid points). Open circles are plots used in this study for development of the density management diagram.

Maximum height, mean height of all trees, and mean height of the tallest 40 TPA (HT40; Flewelling et al. [2001]) were determined using individual tree heights (measured or estimated) and number of TPA. 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 (BA) on a per acre basis for longleaf pine and for all other species combined. Quadratic mean diameter (*Dq*) was calculated from BA and TPA.

We use stand density index (SDI; Reineke [1933]) as an index of relative density because it is essentially independent of stand age and site quality (Curtis 1982, Jack and Long 1996, Williams 1996). SDI is particularly useful for characterizing silviculturally important elements of stand dynamics such as site occupancy and competitive interaction. SDI was calculated using *Dq* (Equation 2) and summation (SDI$_{sum}$; Equation 3):

$$SDI = TPA \cdot \left(\frac{Dq}{10}\right)^{1.6} \qquad (2)$$

where *Dq* is measured in inches at breast height, and

$$SDI_{sum} = \sum \left(TPA \cdot \left(\frac{D_i}{10}\right)^{1.6} \right) \qquad (3)$$

where D_i is the breast height diameter of the *i*th tally tree on the plot and TPA$_i$ is the number of TPA represented by the *i*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) quantified the relationship between SDI$_{sum}$ and SDI using a Weibull model and showed that the ratio of the two values approaches one for stands that are even-aged. Therefore, we calculated the ratio of SDI$_{sum}$:SDI for the purpose of separating relatively even-aged stands from stands with more complex structures.

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 of less than 0.5 were removed also to eliminate inflated per-acre continuous variables associated with small sampled areas. We also eliminated plots with *Dq* < 2.0 in. Plots

with fewer than 20 TPA were excluded because relatively few (less than 4) trees were measured on some plots (e.g., the current 1/6 ac fixed plot design). In an effort to draw plots from nearly pure, nearly even-aged stands for analysis, we applied two additional filtering criteria: (1) longleaf pine BA 90% or more of total plot BA and (2) SDI$_{sum}$:SDI ≥ 0.95.

Stand variables were analyzed and plotted in various combinations in an effort to identify unusual conditions and outlying values. The final number of plots retained for analysis was 343; these were distributed approximately in proportion to the distribution of all FIA plots on which longleaf pine was present (Table 1 and Figure 1).

Nearly all of Bailey's ecoregion sections (Cleland et al. 2004) within the range of longleaf pine are represented in the analysis data. Although eastern Texas is poorly represented, most of the longleaf range in eastern Texas is located in Bailey's ecoregion section 232F (Outer Coastal Plain Mixed Forest, Coastal Plain, and Flatwoods–Western Gulf; Cleland et al. [2004]), which is relatively well represented by analysis plots located in the Louisiana portion of the section. In east central Alabama and northwestern Georgia, analysis plots were essentially absent from ecoregion sections 231A and 231D (Southern Appalachian Piedmont and Southern Ridge and Valley; Cleland et al. 2004), reflecting the limited longleaf pine dominance in the forests of those sections. The high number of total plots and high proportion of analysis plots in Florida are due to the extensive acreage of longleaf stands found in the western Panhandle. We consider the analysis data set to be representative of nearly pure, nearly even-aged longleaf pine stands across the species' native range. Therefore, our DMD should be representative of longleaf pine throughout its range.

Construction of the Diagram

There are several alternative formats for DMDs (Jack and Long 1996) and we have chosen one with *Dq* and TPA on the major axes (Figure 2) and relative density represented by SDI (Equation 2). This format has been used for DMDs constructed for lodgepole (*Pinus contorta* Dougl. ex. Loud.), slash, loblolly, and ponderosa pines (*Pinus ponderosa* Laws.; McCarter and Long [1986], Dean and Jokela [1992], Dean and Baldwin [1993], Williams [1994], Long and Shaw [2005]).

We assume an SDI of 400 to be a reasonable approximation of longleaf pine maximum size density, i.e., the theoretical boundary for combinations of mean diameter and density. The largest SDIs represented in our data set are about 400 (Figure 3). This also is the maximum SDI that Reineke (1933) found for longleaf pine.

In addition to the SDI lines, the DMD (Figure 2) has a family of curves representing top or site height (i.e., the average height of the "site trees," the dominant and codominant trees used in estimating site index). Equation 4 was fit with nonlinear regression to relate *Dq* to TPA and the tallest 40 TPA (HT40):

$$Dq = 2.02 + (0.004 - 0.002 * TPA^{0.1}) \cdot HT40^2 \qquad (4)$$

where HT40 is the mean height of the tallest 40 TPA, and *Dq* and TPA are defined mentioned previously.

The model has an estimated R^2 of 0.96 and a standard error of 0.03 in. Examination of residuals suggests that the model is unbiased with respect to the predictor variables as well as site index, SDI, volume, and BA.

A third set of lines, representing gross stand volume (VOL), was generated using a nonlinear regression model (Equation 5) relating VOL, *Dq*, and TPA:

Table 1. FIA surveys conducted in states within the range of longleaf pine and number of plots on which longleaf pine occurs.

State	Years (type)	Longleaf plots	Plots used	% Used
Alabama	1990 (p), 2000 (p), 2001–2003 (a)	737	27	3.7
Florida	1987 (p), 1995 (p)	1,567	151	9.6
Georgia	1989 (p), 1997 (p), 2001–2003 (a)	1,010	65	6.4
Louisiana	1991 (p), 2001–2003 (a)	204	12	5.9
Mississippi	1994 (p)	254	9	3.5
North Carolina	1984 (p), 1990 (p), 2002 (p)	449	29	6.5
South Carolina	1986 (p), 1993 (p), 1997–2001 (a)	931	49	5.3
Texas	1992 (p), 1999–2003 (a)	70	1	1.4
Virginia	1984 (p), 1992 (p), 1997–2001 (a)	0	0	n/a

a, Annual inventory; p, periodic inventory.

$$VOL = -232 + 0.03\ TPA \cdot Dq^{2.6} \qquad (5)$$

where VOL is gross cubic-foot volume per acre, and Dq and TPA are defined as mentioned previously.

The model has an estimated R^2 of 0.94 and a standard error of 14 ft^3/ac. Examination of residuals suggests that the model is unbiased with respect to the predictor variables as well as site index, SDI, and BA. As with Equation 4, there were no apparent biases associated with geographic origin of the data.

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.

Maximum Size–Density Relationship

A maximum size–density relationship represented by an SDI of 400 is consistent with our data except for stands with somewhat larger mean size (Figure 3). Reineke's (1933) display of Dq versus TPA for longleaf pine also suggested a departure from a constant size–density relationship for stands of large average diameter. Indeed for many species, older self-thinning stands appear to fall away from the size–density boundary (White and Harper 1970, Cao et al. 2000). Zeide (2005) suggests that self-thinning, in fact, has two components. The first is caused by increasing mean size (e.g., Equation 2), and the second is associated with the inevitable accumulation of canopy gaps in mature stands. He associates the accumulation of gaps with decreasing self-tolerance in mature stands. White and Harper (1970) attribute the apparent change in the size–density boundary to the inability of old, large trees to fully recapture available resources after the death of other large trees. At least in part, the phenomenon may result from increasing mechanical abrasion and resulting crown shyness as tree heights increase (Putz et al. 1984, Long and Smith 1992). The boundary that is effectively established by the fall-off phenomenon presents a real limitation to managers, especially in cases where natural stand conditions are desirable. To distinguish this limit from the one represented by maximum SDI, we will use the term "mature stand boundary" (MSB).

There are several approaches to defining boundaries in size–density relationships (Bi and Turvey 1997, Bi et al. 2000). In most cases, these efforts have applied linear models to estimate the slope and intercept of the self-thinning relationship (e.g., Pretzsch and Biber [2005]). The use of long-term remeasurement data, such as used by Pretzsch and Biber (2005), is rare; therefore, approaches to establishing maximum density functions usually involve censoring the data in such a way as to remove observations of low relative density and fitting a model to the remainder. In our case, the pattern of fall-off appears to be nonlinear in log-log space and we wish to include some observations representing low relative density in the analysis. Given this situation, common censorship methods, such as taking the highest few percent of observations (Edminster 1988), would not be applicable. We also felt that the data set used to develop the DMD would be too small to describe adequately the boundary. Therefore, we used the following steps to estimate the MSB:

1. We relaxed the composition and even-agedness criteria of the FIA data set to 60% longleaf BA and SDI$_{sum}$:SDI ratio to 0.5. We also set the minimum Dq to 4.0 in., because stands in this size range are not needed to establish the MSB.
2. We took the plot with the highest observed SDI (or TPA) in each 0.1-in. class of plot Dq, yielding 102 size–density observations.
3. We fitted a four-parameter function to these observations:

$$Dq = 18.68 - 20.63(e^{-13.25\,TPA^{0.503}})$$
$$(n = 102;\ R^2 = 0.87) \qquad (6)$$

4. We shifted the curve developed in step 3 such that most of the observations would lie inside the curve. Dividing the SDI of points on the fitted curve by 0.7 produced a shifted curve that was exceeded by less than 3% of the observations used to fit the original curve.

We believe that the MSB developed by this process is a good approximation of the practical limit to the size–density relationship for longleaf pine. FIA data are geographically comprehensive and should show no bias with respect to the range of longleaf stand conditions—stand conditions are represented in the data approximately in proportion to their abundance on the landscape. Comparison of the MSB to several independent data sets revealed only one exception, representing a single plot (Figure 4).

Objectives sometimes will require density management of mature longleaf pine stands. We think it important, therefore, to recognize the fundamental change in the size–density relationship of mature longleaf pine stands. The final DMD (Figure 2) includes representation of what we consider the MSB for longleaf pine as a species. However, we suspect that the MSB may be more restrictive in some cases, such as in stands growing on very dry or very wet sites. Local inventory data may be used to determine if a lower MSB may exist on particular sites.

Relative Density Thresholds

We suggest that the 250 SDI line on the DMD represents a threshold for the self-thinning zone (characterized as the zone-of-imminent-competition-mortality by Drew and Flewelling [1979]).
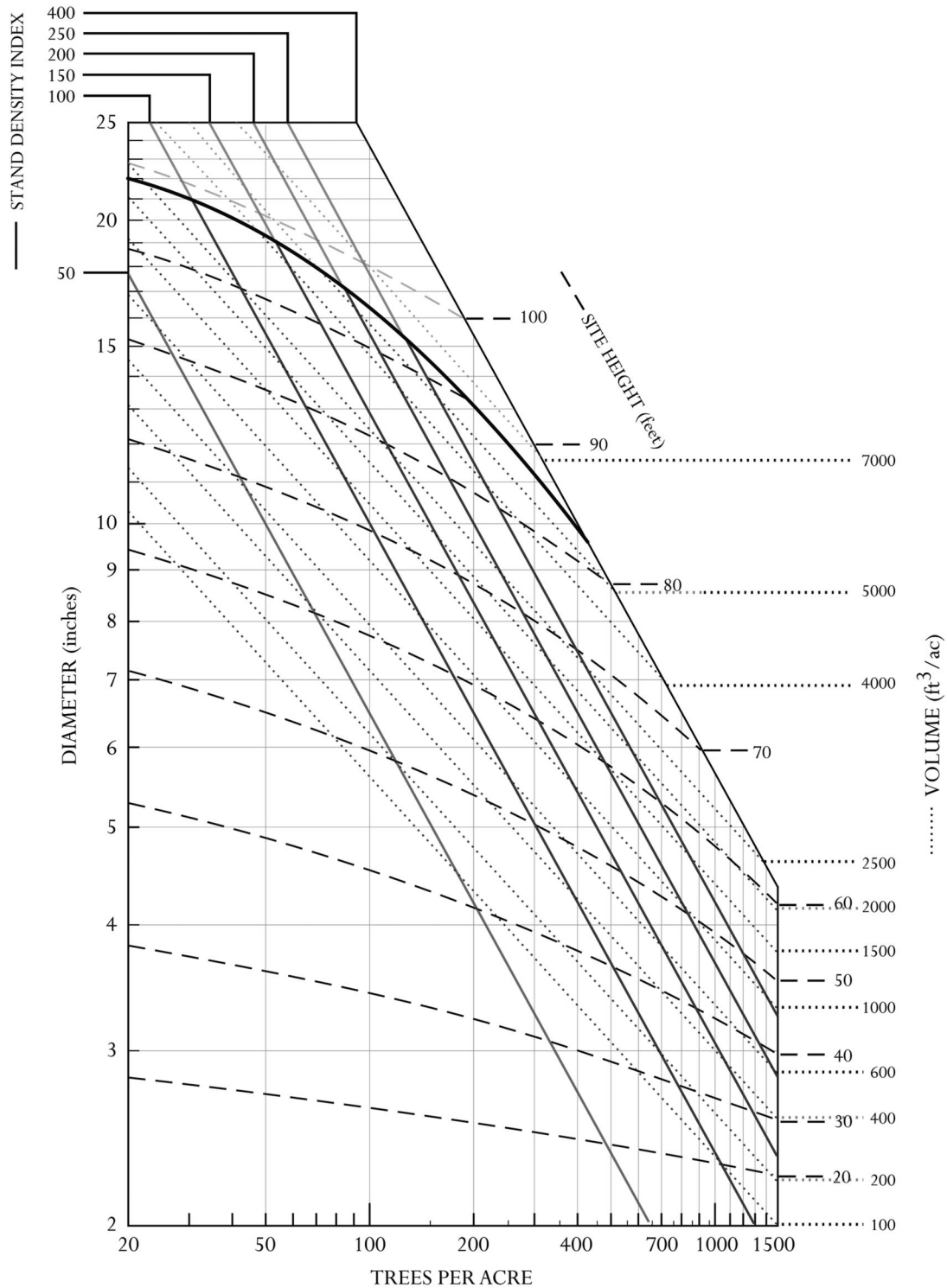
Figure 2. A density management diagram for even-aged longleaf pine stands.

As a percent of SDI$_{max}$, 250 is only slightly greater than 60%, a figure that generally has been associated with the onset of self-thinning (Long 1985). In terms of relative density, 25% of SDI$_{max}$ generally has 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 (Drew and Flewelling 1979). An SDI of 100 also may approximate a threshold where the overstory begins to have significantly negative effects on the understory. For example, results from a study of establishment and recruitment of the wiregrass *Aristida beyrichiana* Trin. & Rupr. in a longleaf plantation (Mulligan et al. 2002) suggest that thinning to a relative density less than 25% of SDI$_{max}$ significantly improved understory restoration. We assume an SDI of 140 is a reasonable estimate of the lower limit of full site occupancy for longleaf pine. For several species, 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).
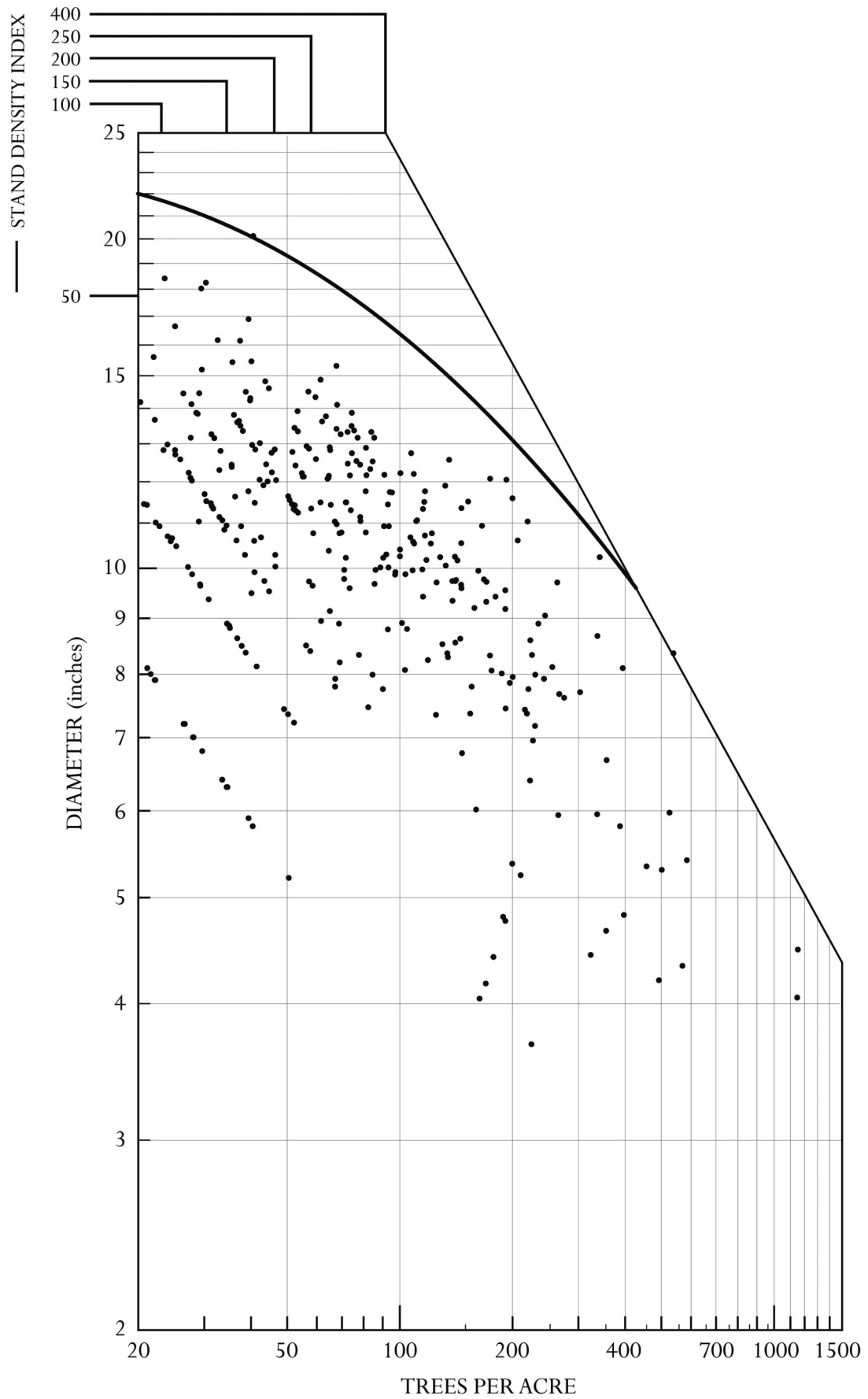
Figure 3. Plots used in this study plotted in size–density space.
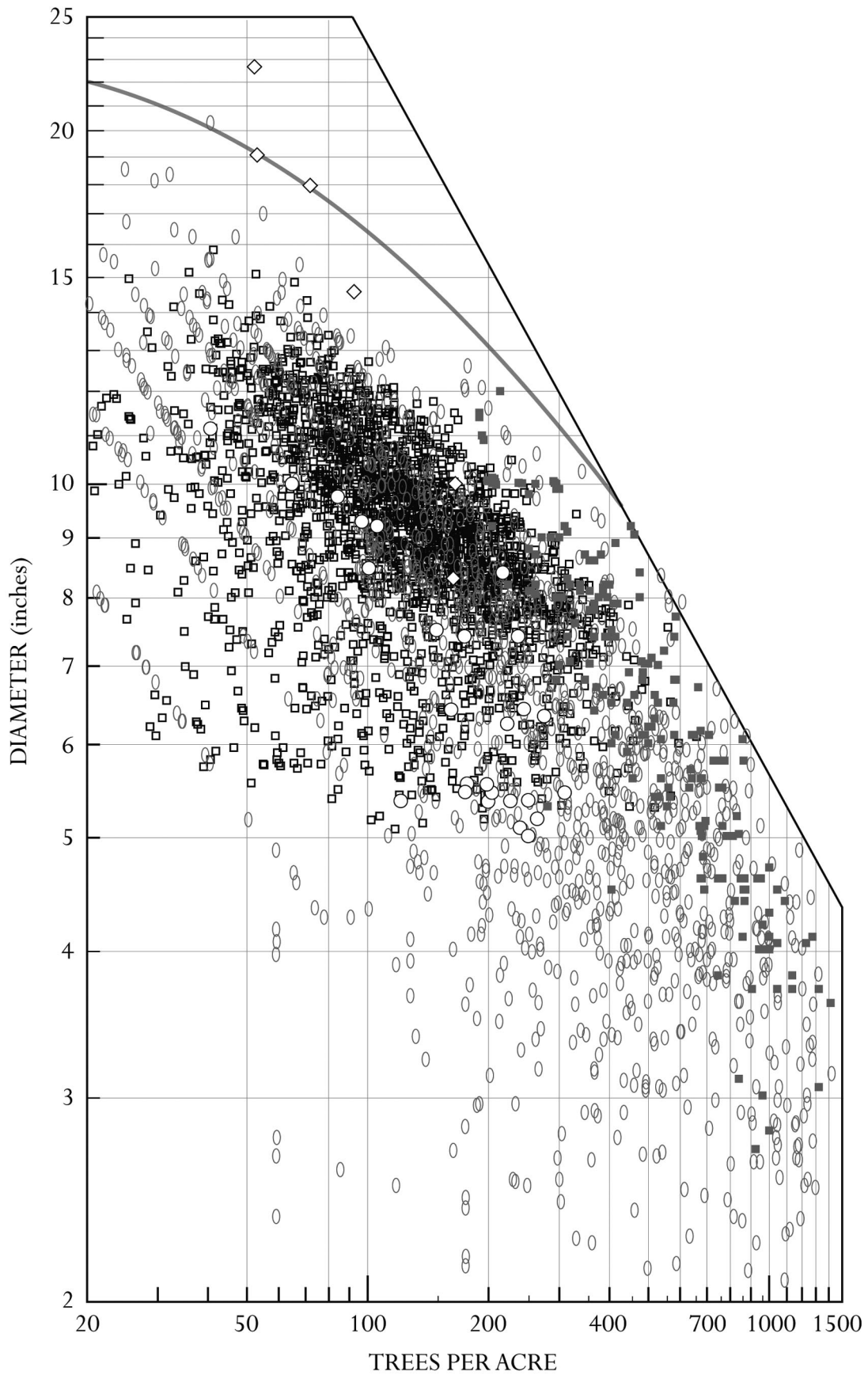
Figure 4.   MSB and selected longleaf pine size–density data. Data include longleaf-dominated stands in the FIADB (oval), stands from Fort Bragg, North Carolina (open square), Sandhills National Wildlife Refuge, South Carolina (circle), Schwarz's (1907) stand tables (diamond), and Reineke (1933; solid square). The point exceeding the MSB is based on 26 trees measured on 0.5 ac (Schwarz 1907).

Table 2. Definition of good-quality RCW foraging habitat according to the RCW recovery plan.

Habitat criterion	Definition
a	There are 18 or more stems/ac of pines that are more than 60 yr in age and more than 14 in. dbh. Minimum BA for these pines is 20 ft^2/ac. Recommended minimum rotation ages apply to all land managed as foraging habitat.
b	BA of pines 10–14 in. dbh is between 0 and 40 ft^2/ac.
c	BA of pines less than 10 in. dbh is below 10 ft^2/ac and below 20 stems/ac.
d	BA of all pines more than 10 in. dbh is at least 40 ft^2/ac; i.e., the minimum BA for pines in categories a and b is 40 ft^2/ac.

Source: US Fish and Wildlife Service 2003, 188.

Discussion

Stand Assessment and Use of the Diagram

Examples of using DMDs for planning routine density management regimes, such as attaining a desired end-of-rotation mean diameter with one or more intermediate treatments can be found elsewhere (e.g., McCarter and Long [1986] and Dean and Baldwin [1993]). The mechanics of such applications are essentially invariant among DMDs. To illustrate use of the longleaf pine DMD, we show options for managing longleaf pine stands that are consistent with the recovery guidelines for the RCW (US Fish and Wildlife Service 2003). This example is a restoration scenario, where the manager is presented with a well-stocked longleaf stand and the management goal is to create future stand structure that is considered "suitable habitat" under the recovery guidelines. We emphasize that this example addresses only stand structure (i.e., size and number of trees) and dynamics over variable-length time periods. We do not explicitly address issues, e.g., of understory vegetation, application of fire, or availability of suitable cavity trees.

The current recovery guidelines for the RCW (US Fish and Wildlife Service 2003) address multiple aspects of habitat, including desirable stand structure and the silvicultural systems that can be used to create and maintain it (US Fish and Wildlife Service 2003, 99). For some habitat characteristics it is possible to delineate boundaries or zones in size–density space on a DMD (Smith and Long 1987, Lilieholm et al. 1994, Long and Shaw 2005). The RCW recovery plan lists stand characteristics that constitute good quality RCW foraging habitat (US Fish and Wildlife Service 2003, 188). Four of these concern overstory stand structure and are addressed in this study (Table 2). Our methods for delineating the size–density zone in which these characteristics are present are provided in detail in the appendix. A DMD with the suitable habitat zone (Figure 5) can be used for evaluation of alternative management scenarios.

Managing Density for Suitable RCW Habitat

In this example we make no attempt to place any qualitative value on stands; stands are treated according to the guidelines in a "black-and-white" manner, i.e., either suitable or not. We use a hypothetical, well-stocked (500 TPA) stand located on the Gulf Coast, with a site index of 75 ft at 50 years base age. Our objective is to evaluate alternative management regimes with respect to achieving and maintaining desirable RCW foraging habitat. Stand conditions represented by the DMD are essentially independent of age and site quality. However, site quality determines the time required for a stand to attain a given size and, therefore, the time required to reach a desired point on the DMD. Because stand top height lines have been incorporated into the DMD, site index curves may be used to approximate the time required to reach desired stand conditions.

We selected Farrar's (1981) site index equation for longleaf pine in the Gulf States, as modified by Rayamajhi et al. (1999), to use in this example. This equation was developed for naturally regenerated, even-aged stands and uses a base age of 50 years. We selected this equation because it was fitted using data from age classes up to 110 years (Rayamajhi et al. 1999), eliminating the need to extrapolate the curves in the example. Other site index curves for longleaf pine are designed for plantations or natural short-rotation stands and may only extend to 25 or 35 years of age (e.g., Cao et al. [1997] and Boyer [1980]). As a result, they are not useful for evaluation of the mature stand conditions specified in the RCW recovery guidelines. If curves of the latter type are the only ones available locally, extrapolation should be done with caution or locally appropriate curves should be developed. Another potential limitation of using some site index curves exists because of varying definitions of stand top height. Sharma et al. (2002) found significant differences between the top height values produced by different definitions. In our example, Farrar's (1981) equation uses average height of dominant and codominant trees, which may lead to overestimation of age when using HT40 in place of the intended top height definition.

In a no-management scenario stand density is expected to remain unchanged until the stand approaches the lower limit of self-thinning (SDI = 250; Figure 5, line A). At this relative density, self-thinning should begin when stand top height is between 60 and 70 ft, which translates, using the site index curves as mentioned previously (Rayamajhi et al. 1999), to approximately 35 years of age. Because of excessive density, the stand does not cross into the zone of suitable RCW habitat until top height is approximately 90 ft, or at about 150 years of age and 13.5-in. Dq. At this point, stand dynamics also are transitioning from competition-induced self-thinning to the MSB.

It is possible to move this stand into the suitable habitat zone much sooner than the 150 years projected in the no-management scenario. Cumulative BA calculations show that this stand will meet the BA criteria for trees 10 and 14 in. or more by the time Dq reaches 11 in. but fails to qualify as suitable habitat because of excessive BA in stems less than 10 in. Should the stand be found in this condition, it can be moved quickly to suitable structure by removing small stems with a low thinning. Assuming the stand is entered when Dq is 11 in., this means reducing absolute stem density from about 250 to 120 TPA or less (100 TPA shown; Figure 5, line B). Although this intervention occurs relatively late in stand development (80–85 years of age), it simultaneously increases stand vigor and reduces the time required to reach suitable condition by 65–70 years. This is the difference between time of intervention (stand top height = 83 ft) and the time an untreated stand reaches the suitable zone (stand top height = 90 ft).

If earlier intervention is possible, the stand can be thinned to a density that will put it on a trajectory to achieve suitable structure in the shortest time possible. According to the diagram, minimum stand dimensions are indicated by the lowest edge of the suitability zone, where
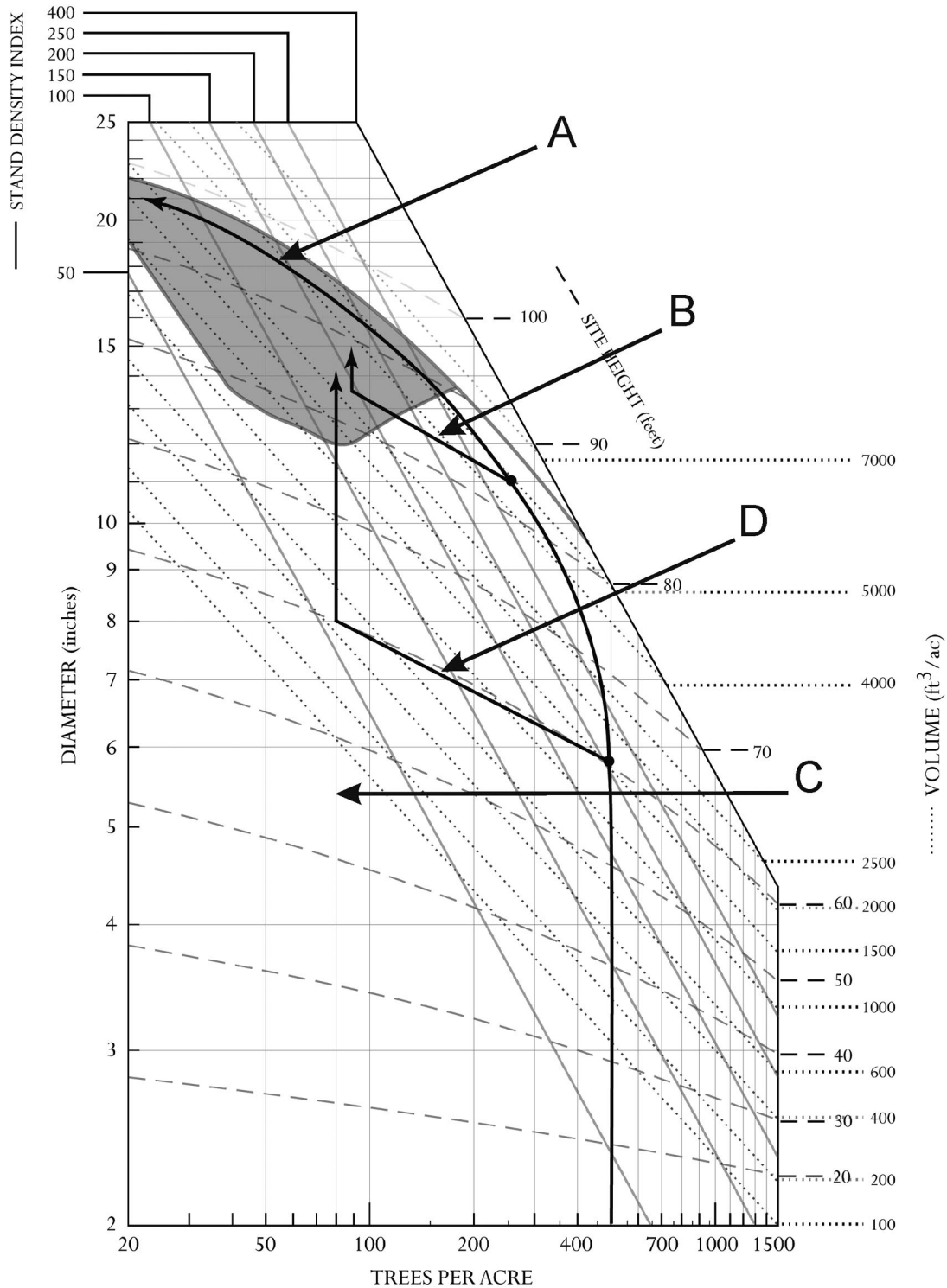
Figure 5. Illustration of alternative density management regimes used to create and maintain suitable RCW foraging habitat. (A) Unmanaged stand trajectory. (B) Late thinning to increase stand suitability. (C) Stem density at which stand structure reached suitable conditions at earliest possible age. (D) Early thinning to set stand on trajectory for earliest possible suitability.

Dq is 12 in. and stand top height is approximately 77 ft. The postthinning density target can be determined by dropping a vertical line from the lower edge of the suitability zone to the x-axis of the DMD (Figure 5, line C). The DMD shows that thinning down to approximately 80 TPA would achieve the desired size earliest. Timing of the thinning is not critical, other than that it should occur before self-thinning begins and, ideally, when stand conditions make it commercial. In our alter-native, the stand has been allowed to develop to a point just short of self-thinning to encourage crown lift and clear boles, is thinned to 80 TPA, and is allowed to develop naturally thereafter (Figure 5, line D). Early intervention reduces the time required to reach suitable habitat structure by another 20–25 years over the late intervention scenario. In addition, the stand is maintained in vigorous condition for the entire period by avoiding excessive relative density (i.e., SDI < 250).

Note that a given point on the DMD may represent different stand conditions, depending on stand history. For example, the two thinning regimes appear to produce approximately the same stand conditions when *Dq* is about 14 in. However, actual stand structure will differ because of the difference in timing of the thinning. The stand thinned later (Figure 5, line B) is expected to have narrower crowns because it was in a self-thinning stage at the time of treatment and crowns have had little time to recover by the time *Dq* approaches 14 in. A timely thinning (Figure 5, line D) should allow leaf area and crown width ample time to recover before the stand reaches the RCW zone. Also, diameter distributions of the stands will differ somewhat, with the late thinning producing a narrower distribution as a result of recent removal of smaller trees during the thinning. Another difference may be that trees in the late thinning regime may have a higher proportion of heartwood than trees thinned earlier. These differences may warrant consideration in terms of potential effects on RCW habitat characteristics.

We also should note that the time savings from thinning are approximate. The site index curves we used (Rayamajhi et al. 1999) are relatively flat for mature stands, resulting in our example, in an estimated 65–70 years for the stand to grow from 83 to 90 ft. Also, differences between the stand top height definition use in development of the DMD and local site index curves may account for some prediction error.

Managing Uneven-Aged Stands

Uneven-aged systems are preferred under the RCW recovery guidelines, primarily because they can provide continuous cover and relatively open understory conditions. For a period after regeneration cuts, even-aged systems tend to produce large openings followed by a dense sapling stage. Both conditions are considered unsuitable for the RCW. Although DMDs usually are applied to even-aged stands, they can be used in the design of uneven-aged systems that use group selection. DMDs are not applicable when it is desired to maintain several size–age cohorts in an intimate mixture, as can be done with tolerant species. Therefore, the user may consider our example as an even-aged stand or one-age cohort within a group selection system.

Conclusion

Relationships among *Dq*, TPA, stand volume, and stand top height are generally insensitive to site quality. SDI_{max} and the MSB should be considered maxima for the forest type. There may be situations, such as on very dry or very wet sites, when attainable stand densities may be lower, but the DMD should be broadly applicable in the longleaf pine type.

Our RCW habitat example uses a strict application of the definition of good-quality RCW foraging habitat, according to the current recovery plan (US Fish and Wildlife Service 2003). However, as with all scientific knowledge, we expect understanding of "good-quality" RCW habitat to evolve with time. Changes in the characterization of suitable stand structure can be incorporated easily into the DMD. Likewise, it is possible that as more longleaf pine stands are managed under extended rotations, our understanding of the dynamics of mature longleaf stands and the MSB will improve as well.

Finally, we note that although DMDs are extremely useful tools, they do not replace other growth and yield models, such as the southern variant of the Forest Vegetation Simulator (Johnson 1997, Wykoff et al. 1982). DMDs offer a convenient tool for assessment of stand status and can be easily used to determine starting conditions when designing sophisticated management simulations. Also, DMDs and other models should always be applied using the best local knowledge and silvicultural and ecological insight.

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Appendix

Delineating Suitable RCW Habitat Structure on the DMD

Because RCW habitat suitability criteria specify diameter maxima, minima, or both, depending on the segment of the diameter distribution, delineation of "good foraging habitat" boundaries on the DMD is not straightforward. However, by modeling certain characteristics of even-aged stands it is possible. First, a stand BA boundary can be placed at 40 ft^2/ac according to the minimum BA criterion (Table 2, criterion d). This line is established initially with the caveat that at least 20 ft^2/ac is in trees 14 in. or more in diameter (Table 2, criterion a). Note that a stand that meets the minimum BA requirement may actually have up to 50 ft^2 of BA; BA of trees less than 10 in. do not count toward the minimum BA and only 10 ft^2/ac of trees less than 10 in. are allowed under the definition of good foraging habitat (Table 2, line c). Criterion a of Table 2 specifies that trees 14 in. or more should be at least 60 years old, but it is not necessary to consider age to define the suitable habitat zone on the DMD. Instead, age is assessed with the use of site index curves, as shown earlier in the application example.

Stands that meet the minimum BA may or may not meet the definition of good foraging habitat, depending on the distribution of stem diameters. Therefore, we developed cumulative BA curves using the same data set used to develop the density management
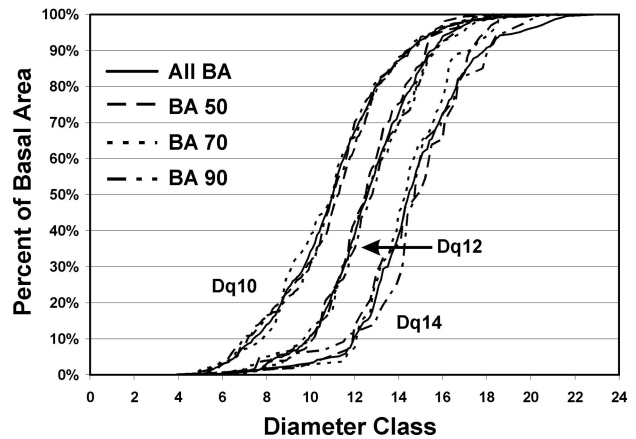

Figure A1. Cumulative BA data for even-aged longleaf pine stands. Only *Dq* classes of 10, 12, and 14 in., and BA classes of 50, 70, and 90 ft^2/ac are shown for clarity.
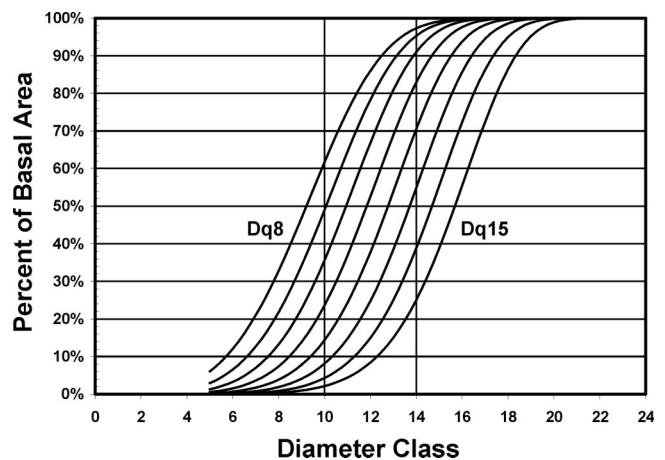

Figure A2. Cumulative BA curves for even-aged longleaf pine stands with *Dq* of 8–15 in.

diagram. We developed a matrix by assigning FIA plots to 1-in. mean diameter classes and 10-ft^2 BA classes. All plot data in each matrix cell were then used to develop cumulative distributions of BA as a function of diameter class (Figure A1). It is evident that the shape of the BA distribution curves is invariant with respect to the total BA of the stand and that the locations of the curves, as expected, are strongly related to *Dq*.

This relationship allowed us to develop a model of cumulative BA as a function of *Dq* and stem diameter class (Figure A2). We modified an equation originally developed to model chemical saturation curves (Morgan et al. [1975]; Equation A1), because it provided the necessary flexibility:

$$\%BA = 100 \cdot e^{-(10^{0.491 - 0.032 DIA^{1.266}})(Dq^{-1.406 + 0.917 DIA^{0.848}})} \qquad (A1)$$

where %BA is the proportion of stand basal area, as mentioned previously, above the target diameter; DIA is the target diameter; and *Dq*, as mentioned previously, is the quadratic mean stand diameter ($n = 871$; $R^2 = 0.99$).

Using stand BA and *Dq*, both of which are commonly available or easily obtained stand variables, it is possible to estimate the amount of BA in any range of diameters. This approach may be used mathematically (Equation A1) or graphically (Figure A2).

Table A1. Attainment of RCW foraging habitat stand structure criteria for selected mean stand diameters and total BAs.

Dq	40	45	50	55	60	65	70	75	80
					Stand BA/ac (ft^2)				
A									
8	15.3	17.2	19.2	21.1	23.0	24.9	26.8	28.7	30.7
9	20.4	23.0	25.5	28.1	30.6	33.2	35.7	38.3	**40.8**
10	25.8	29.0	32.2	35.4	38.7	**41.9**	**45.1**	**48.3**	**51.5**
11	30.6	34.4	38.2	**42.0**	**45.8**	**49.7**	**53.5**	**57.3**	**61.1**
12	34.3	38.5	**42.8**	**47.1**	**51.4**	**55.7**	**59.9**	**64.2**	**68.5**
13	36.8	*41.4*	*45.9*	*50.5*	*55.1*	*59.7*	*64.3*	*68.9*	*73.5*
14	38.3	*43.1*	*47.9*	*52.6*	*57.4*	*62.2*	*67.0*	*71.8*	*76.6*
15	39.1	*44.0*	*48.9*	*53.8*	*58.7*	*63.6*	*68.5*	*73.4*	*78.3*
16	39.6	*44.5*	*49.5*	*54.4*	*59.4*	*64.3*	*69.3*	*74.2*	*79.2*
17	39.8	*44.8*	*49.8*	*54.7*	*59.7*	*64.7*	*69.7*	*74.7*	*79.6*
B									
8	1.1	1.2	1.3	1.5	1.6	1.8	1.9	2.0	2.2
9	1.9	2.1	2.3	2.6	2.8	3.0	3.3	3.5	3.7
10	3.6	4.0	4.5	4.9	5.4	5.8	6.3	6.7	7.2
11	6.8	7.7	8.5	9.4	10.2	11.1	11.9	12.8	13.6
12	11.8	13.3	14.7	16.2	17.7	19.1	**20.6**	**22.1**	**23.6**
13	18.0	*20.3*	*22.5*	*24.8*	*27.0*	*29.3*	*31.6*	*33.8*	*36.1*
14	**24.5**	*27.5*	*30.6*	*33.6*	*36.7*	*39.7*	*42.8*	*45.9*	*48.9*
15	**30.0**	*33.7*	*37.5*	*41.2*	*45.0*	*48.7*	*52.4*	*56.2*	*59.9*
16	**34.0**	*38.3*	*42.5*	*46.8*	*51.1*	*55.3*	*59.6*	*63.8*	*68.1*
17	**36.7**	*41.3*	*45.9*	*50.5*	*55.0*	*59.6*	*64.2*	*68.8*	*73.4*
C									
8	24.7	27.8	30.8	33.9	37.0	40.1	43.2	46.3	49.3
9	19.6	22.0	24.5	26.9	29.4	31.8	34.3	36.7	39.2
10	14.2	16.0	17.8	19.6	21.3	23.1	24.9	26.7	28.5
11	**9.4**	10.6	11.8	13.0	14.2	15.3	16.5	17.7	18.9
12	**5.7**	**6.5**	7.2	7.9	8.6	9.3	10.1	10.8	11.5
13	**3.2**	*3.6*	*4.1*	*4.5*	*4.9*	5.3	5.7	6.1	6.5
14	**1.7**	*1.9*	*2.1*	*2.4*	*2.6*	*2.8*	*3.0*	*3.2*	*3.4*
15	**0.9**	*1.0*	*1.1*	*1.2*	*1.3*	*1.4*	*1.5*	*1.6*	*1.7*
16	**0.4**	*0.5*	*0.5*	*0.6*	*0.6*	*0.7*	*0.7*	*0.8*	*0.8*
17	**0.2**	*0.2*	*0.2*	*0.3*	*0.3*	*0.3*	*0.3*	*0.3*	*0.4*

Boldface represents combinations of *Dq* and BA that satisfy individual criteria for the suitable forage habitat definition (A: BA/ac in stems 10 in. or greater (Table 2, criterion d); B,: BA/ac in stems 14 in. or greater (Table 2, criterion a); C, BA/ac in stems less than 10 in. (Table 2, criterion c). Values for criterion b in Table 2 are not shown, but the values may be calculated but subtracting the cells in B from A. All cells in the ranges of *Dq* and BA in meet criterion b in Table 2. Boldface italic represents conditions that simultaneously satisfy criteria a–d.

On the DMD we are interested in establishing a threshold that simultaneously meets the requirement of 40 ft^2 or more BA in trees 10 in. dbh or more and 20 ft^2 or more BA in trees 14 in. or more, while not exceeding the 10 ft^2 of BA allowed in trees less than 10 in. For stands with large *Dq* and relatively low density, the threshold is coincident with the 40-ft^2 minimum BA line. Points along the lower boundary may be found by evaluating the proportions of stand BA allocated to each of the three zones (zones A–C) in Table A1. Calculated values for each of the criteria, for selected ranges of *Dq* and BA, are provided in Table A1, and the threshold values are represented on the DMD as the lower edge of the suitability zone (Figure 5). Note that the habitat threshold is curvilinear and tangent to the line representing *Dq* = 12 in. between 80 and 90 TPA. As TPA decreases from 90 to about 40, the minimum *Dq* increases because it is necessary to increase the proportion of the diameter distribution above 14 in. to meet the habitat criteria. Mimimum *Dq* increases to about 14 in., at which time the line crosses the minimum allowable total stand BA of 40 ft^2/ac. The increase in minimum *Dq* that occurs over 90 TPA is caused by the increasing amount of BA contributed by trees less than 10 in. dbh. The resulting suitable habitat zone (Figure 5, shaded area), as defined by the RCW recovery guidelines (US Fish and Wildlife Service 2003), is bounded by the 40 ft^2/ac BA minimum, the threshold defined by minimum BA and acceptable diameter distribution, and the MSB established earlier.