A NEW TYPE OF DENSITY-MANAGEMENT DIAGRAM FOR SLASH PINE PLANTATIONS

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Abstract—Many Density-Management Diagrams (DMD) have been developed for conifer species throughout the world based on stand density index (SDI). The diagrams often plot the logarithm of average tree size (volume, weight, or quadratic mean diameter) over the logarithm of trees per unit area. A new type of DMD is presented for slash pine (*Pinus elliottii* var *elliottii*) plantations where SDI is plotted over age. This proposed DMD eliminates two existing problems with current DMDs: (1) the need to estimate age from other measures found on traditional DMDs, and (2) a second variable also directly dependent on either age or SDI can be placed on a third axis. Plotting SDI over age clearly shows when thinnings need to be conducted to obtain a certain tree size-density objective both in terms of stand density and age. Yet this proposed DMD does not violate the well-known principle that DMDs are independent of age. Understory models are usually developed using an overstory density measure that includes both trees per unit area and a diameter measure (i.e. basal area per unit area or SDI per unit area) making it difficult to include them on current DMDs. Plotting SDI over age allows understory vegetation development to be easily included on a DMD. This provides a natural resource manager the ability to see what impacts a particular tree size-density objective has on understory vegetation production over time. An understory vegetation model was developed to demonstrate the applicability of the proposed DMD.

INTRODUCTION

The use of stand density index (SDI) in density management diagrams (DMDs) is a useful tool to help achieve desired tree size-volume objectives. Many papers have discussed the theory and reasoning behind SDI and associated DMDs (Dean and Baldwin 1993, Dean and Chang 2002, Dean and Jokela 1992, Drew and Flewelling 1979, Long 1985, Mack and Burk 2002, McCarter and Long 1986, Reineke 1933, Williams 1994). It is not the purpose of this paper to agree or contradict these principles but rather to develop a new way of presenting them.

By plotting SDI over age, two problems with traditional DMDs are eliminated. First, age need not be estimated from other variables (Dean and Baldwin 1993, Dean and Chang 2002, Mack and Burk 2002) for traditional DMDs. This is generally done by placing dominant height curves on traditional DMDs, which can make the graphs rather complex and "busy". Secondly, another variable directly dependent on age or SDI can be more easily included on a third axis. For example, understory vegetation is usually predicted using a measure that includes both tree density per area and stem diameter, such as SDI, and not by using quadratic mean diameter (qmd) and trees-per-acre (tpa) as separate independent variables (Grelen and Lohrey 1978, Moore and Dieter 1992, Wolters 1982, Wolters and Schmidtling 1975). Therefore, it is rather difficult to include understory vegetation on traditional DMDs, which often plot the logarithm of qmd over the logarithm of tpa. This proposed DMD, plotting SDI over ag also presents SDI as stand density development over age, which is familiar to most foresters. This provides a much clearer picture of the age(s) at which thinning(s) should be conducted to obtain a certain tree size-density management objective.

To those familiar with SDI and traditional DMDs, plotting growth trajectories over age may seem contradictory to principles associated with DMDs. It is a tenet of DMDs that they are independent of age (Dean and Baldwin 1993, Long 1985). This can be a somewhat misleading statement. Therefore, a brief explanation of the principles associated with traditional DMDs and how the creation of this new type of DMD relates to them is provided. The proposed DMD is not new because it plots stand density development (represented by SDI) over age, but rather because it also includes the management zones generally associated with DMDs over age as well. No published literature could be found that presents a DMD in this manner. For demonstration purposes, a traditional DMD (Dean and Jokela 1992) developed for slash pine (*Pinus elliottii* Engelm. var. *elliottii*) plantations in the southeastern United States was altered.

DMDs can be created by first determining the Maximum-size density relationship (MSDR) for a particular species (i.e., slash pine) in a specific geographical region (i.e., Southeastern United States): In the case of Dean and Jokela's (1992) slash pine DMD, this is a SDI value of 450 (Dean and Baldwin 1996). Usually, at least two relative numerical values to this MSDR are determined which have various names (Dean and Jokela 1992, Long 1985). Dean and Jokela (1992) determined two relative numerical values to the MSDR which are defined in this current paper as consistent with Long (1985): lower limit of "full-site occupancy" (25 percent of 450 = 112.5), and the lower limit of self-thinning (50 percent of 450 = 225). These values correspond, respectively, to the numerical values of SDI for all slash pine plantations in this region (in theory) where trees begin to fully occupy a site and the point at which competition related mortality due to excessive stand density begins (Dean and Jokela 1992, Long 1985).

When it is stated that SDI is independent of age, foresters are referring to the MSDR and the two relative management zones. Thus, whenever a stand's SDI growth trajectory enters into 1 of these 2 relative management zones or approaches the Maximum-size density line, whether it is at age 10 or at

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age 35, the underlying principles behind each relative management zone and the Maximum-size density line apply. Site quality, moisture amounts, planting density, thinnings, seedling stock morphology, genetics, competing vegetation, etc. all play a role in what age plantation growth trajectories first enter these relative management zones, how long trajectories remain in these relative management zones, and the age at which growth trajectories begin to approach the Maximum-size density line. Kumar and others (1995) presents a more complete description of how age relates to the MSDR and relative management zones.

DERIVATIONS AND DISCUSSION

A DMD developed by Dean and Jokela (1992) for slash pine was manipulated by placing age as the independent variable and SDI, calculated using equation (1), as the dependent variable:

$$SDI = tpa*(qmd/10)^{1.6} \qquad (1)$$

where

tpa = trees-per-acre

qmd = quadratic mean diameter (inches)

The MSDR, the relative numerical values of the Lower limit of "full site occupancy", and the Lower limit of self-thinning to the MSDR are maintained. Data from a long-term slash pine planting density trial in Georgia were used to demonstrate SDI development (Jones 1987). Planting densities were 1,210 tpa (6 feet x 6 feet), 907 tpa (6 feet x 8 feet), 871 tpa (5 feet x 10 feet), 681 tpa (8 feet x 8 feet), 605 tpa (6 feet x 12 feet), 436 tpa (10 feet x 10 feet), 387 tpa (7.5 feet x 15 feet), and 194 tpa (15 feet x 15 feet). Measurement ages were 10, 15, 20, 25, and 30 years. As seen in figure 1, the new type of DMD provides the same information as traditional DMDs as to when stands are within the three management zones.

There may be some question when plotting SDI over age whether self-thinning can be graphically determined. Self-thinning is defined as when plantations are experiencing competition-induced mortality (Mack and Burk 2002) brought about by excessive stand density. This phenomenon is assumed to begin when a stand's SDI growth trajectory enters the Lower limit of self-thinning management zone. On traditional DMDs, generally a stand growth trajectory moving vertically (parallel to the y-axis) indicates the plantation is not self-thinning, while a stand growth trajectory that is moving to the left indicates a plantation is self-thinning. What about on the new type of DMD? It appears that generally, stand growth trajectories that parallel the x-axis (age) or that are moving down on the new type of DMD are self-thinning (fig. 1) when compared to the traditional DMD.

Two long-term planting density studies for loblolly pine (*Pinus taeda* L.) were examined using a DMD developed by Dean and Baldwin (1993). One study was located in South Carolina (Balmer and others 1975, Buford 1991, Harms and Lloyd 1981, Harms and others 2000), and the other study was located in Louisiana (Sprinz and others 1979). Self-thinning of SDI growth trajectories for both of these studies on the proposed DMD appears similar to the slash pine study when compared to traditional DMDs – parallel to the x-axis or when the trajectory has a downward path.

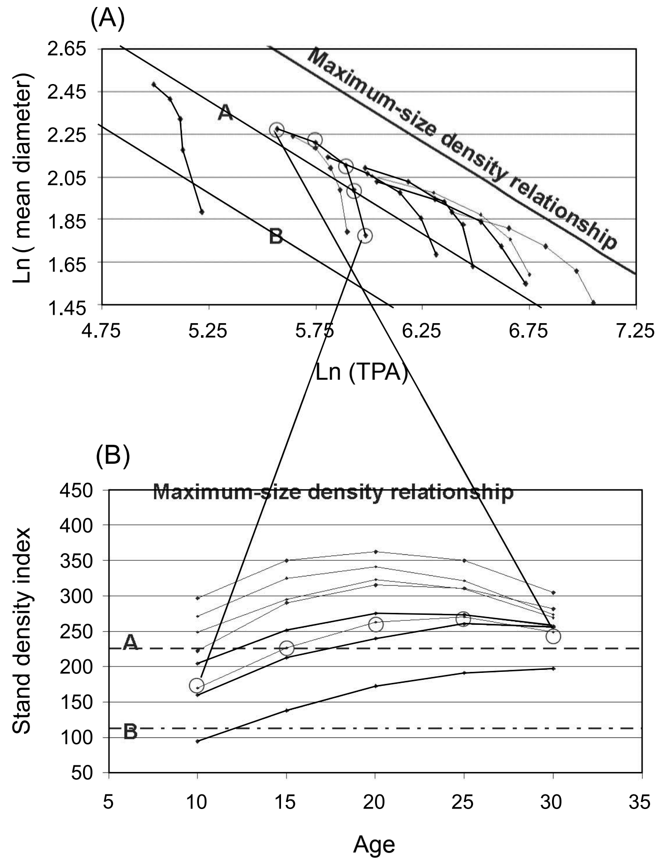

Figure 1—Natural logarithm of quadratic mean diameter in inches [Ln (Mean diameter)] over natural logarithm of trees per acre (LnTPA) (A) and stand density index over age (B) for eight different planting densities of slash pine. Where: A = Lower limit of self-thinning [50 percent of Maximum-Size Density Relationship (MSDR) of 450 = 225], B = Lower limit of "full site occupancy" (25 percent of MSDR of 450 = 112). The circles and connecting lines show how stand development is observed for stands that are either not self-thinning or self-thinning for both types of Density Management Diagrams using the planting density of 436 trees per acre.

Although this is an important consideration, this topic in itself does not invalidate or validate the proposed DMD. The main purpose of the new type of DMD is to provide foresters the ability to graphically see when a plantation's SDI growth trajectory has entered a particular management zone without having to estimate the age at which it occurs.

One disadvantage to using this new type of DMD is the loss of the ability to graphically see the maximum size (qmd)-density (tpa) relationship. By plotting the natural logarithm (ln) of qmd over lntpa, you can see that as tpa decreases, the largest qmd that can occur increases. This is lost on the new type of DMD. Additionally, equation (1) assumes a constant slope (1.6). Many studies have shown the slope can have different values (Tang and others 1994, VanderSchaaf 2004, Zeide 1985) than the 1.6 proposed by Reineke (1933). Therefore, one of the main uses of the new type of DMD may be to help students, landowners, and foresters unfamiliar with DMDs to manage plantations using the principles of the relative management zones. By eliminating the need to estimate age, thus reducing the complexity of DMDs since dominant height curves are not needed, DMDs can be a more useful tool to field managers.

For example, when explaining management regimes to private landowners for their stand's particular growth trajectory, a user can clearly see at what age thinnings need to be conducted to achieve a tree size-density target to meet the landowner's objective. Traditional DMDs can still be used to clarify the maximum-size density principle.

AN APPLICATION OF THE PROPOSED DMD

To better show how the proposed DMD can be useful, estimates of understory vegetation from models presented below were plotted along with overstory density development over age (fig. 2). Estimates of understory vegetation can provide managers information about effects of density on wildlife and domestic grazing animals. By using AUMs and AUM equivalents (VanderSchaaf 1999), managers can quantify how different density management regimes affect the animal carrying capacity of a site. Other publications have used DMDs with SDI to relate stand density to wildlife habitat (Lilieholm and others 1994, McTague and Patton 1989, Smith and Long 1987, Sturtevant and others 1996). Published understory vegetation data were obtained from a long-term unthinned slash pine plantation study located in Georgia (Lewis 1989). Overstory density (tpa and qmd) and herbaceous vegetation production (pounds per acre) were measured annually beginning at age 8 until age 26. Herbaceous vegetation was divided into two lifeforms, grasses and grass-likes (i.e., *Cyperus* spp.) or forbs. Ordinary least squares models (equations 2 and 3) were developed using SDI as the independent variable:

$$\text{grass} = 8561.277 - 1479.530*\ln(\text{SDI}) \quad (2)$$

where

n = 19
MR = mean absolute value of the residual - (Σ|actual – predicted|)/n or in this case 164.7 pounds per acre)
Adj. R^2 = 0.8767
grass = production (pounds per acre) of grasses and grass-likes
ln = natural logarithm

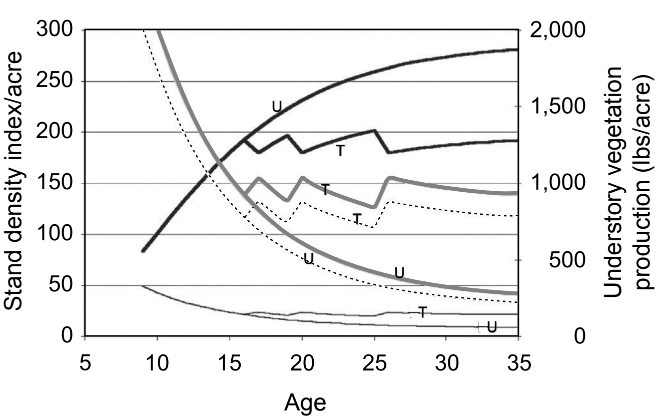

Figure 2—Stand density index and understory vegetation production over age. The dark solid line is overstory stand density development, the gray solid line is total understory herbaceous vegetation production (grasses, grass-likes, and forbs), the dashed lighter line is grass and grass-like vegetation production, and the solid lighter line is forb vegetation production. U = unthinned, T = thinned.

$$\text{forb} = 1305.267 - 221.155*\ln(\text{SDI}) \quad (3)$$

where

n = 19
MR = 57.0 pounds per acre
Adj. R^2 = 0.5822
forb = production (pounds per acre) of forbs

SDI was checked to make sure that it was significant at the $\alpha = 0.05$ level. Many different model forms were tested that included ln, square-root, and exponential transformations of the dependent and independent variables as well as simple straight linear regressions. The final model form selected was based on the MR, error residual trends, and biological correctness of the coefficients. Error residuals showed no adverse trends for the final model form selected. Qmd and tpa as individual independent variables were not significantly different from 0 ($\alpha = 0.05$) using any model form. Yet SDI explained a substantial amount of variation in understory vegetation. This is in agreement with my previous experience with understory vegetation modeling (VanderSchaaf 1999). Of course this is somewhat counterintuitive because it makes sense that a stand with a SDI of 150 composed of 6,000 tpa and a qmd of 1 inch would have a different impact on understory vegetation production than a stand with an SDI of 150 composed of 150 tpa and a qmd of 10 inches. Nonetheless, since traditional DMDs plot lnqmd over lntpa, it is hard to include estimates of understory vegetation on them because of the statistical insignificance of lnqmd and lntpa in understory vegetation models.

A natural resource manager can get a clear picture of how a particular tree size-density objective would affect understory vegetation over time in unthinned and thinned stands (fig. 2). In order to predict understory vegetation production following thinning, equation (4) (Pienaar and Harrison 1989) was developed to estimate stand density production over time using SDI data from Lewis (1989):

$$\text{SDI} = \text{PrevSDI}*[(1-\exp[-0.146*\text{Age}])/(1-\exp[-0.146*\text{Prevage}])\text{^}3.979 \quad (4)$$

where

n = 18
MR = 3.3
Adj. R^2 = 0.9941
PrevSDI = SDI at the previous measurement age
Prevage = previous measurement age

Residual errors showed no adverse trends. Despite being developed using unthinned data, this model allows us to reasonably predict stand density development after thinning so that we can estimate understory vegetation response following this treatment. Information obtained from figure 2 can provide valuable information about wildlife habitat, such or fuel management for fire control, etc. As an example: A forester wants to maintain a relative overstory density between 40 (180 SDI) and 45 percent (202 SDI) of the MSDR up to age 35. Figure 2 shows that thinning can greatly increase herbaceous production based on the equations presented in this paper. At age 35, total herbaceous production in the thinned stand is 646 pounds greater than total herbaceous production in the unthinned stand on a per acre basis. Managers can use the proposed DMD to adjust stand density to meet an overstory requirement as well as to achieve an understory vegetation objective.

Some researchers have modeled understory production as a function of age (Mengak and others 1989). Although this approach may have applicability (perhaps due to different nutrient requirements of trees through time, etc.), stand density impacts understory production much more than stand age. For instance, understory production at age 5 in 2 stands where 1 stand was planted at 300 tpa and the other was planted at 2,500 tpa would most certainly be greater in the 300 tpa planted stand. In a model using age as a regressor, age would be a surrogate for stand density, although only a useful surrogate within a limited range of stand densities. The DMD proposed in this paper could relate understory production to SDI, and then by relating SDI to age, one could obtain an estimate of understory production at various ages (fig. 2). More complex understory models could examine specific understory species production relative to overstory stand density. This proposed type of DMD can be developed for plantations and perhaps for naturally regenerated even-aged stands of any overstory species or combination thereof. It should be remembered that either type of DMD (traditional or the type proposed here) does not take into account economics and is most useful to those who want to achieve a certain tree size-density objective to meet management criteria. Other variables dependent on SDI or age could be included on the proposed DMD. For example, perhaps coarse-woody debris amounts could be plotted over age to provide a clear picture of how overstory density affects decomposition over time.

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