A PRELIMINARY WHITE SPRUCE DENSITY MANAGEMENT DIAGRAM FOR THE LAKE STATES

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Staff Paper Series No. 145

DEPARTMENT OF FOREST RESOURCES

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A density management guideline (DMD) is an improvement of the traditional stocking chart that is empirically calculated and ecologically based. It can provide a tool for managers to

habitat). Using measurements from 22 white spruce plantations, scattered across northern Minnesota, northern Wisconsin, and the upper peninsula of Michigan, we developed a DMD

managers in making thinning and harvesting decisions in young white spruce plantations. Ongoing research will refine this DMD to better isolate both zones of maximum timber

DMD in native and larger-diameter stands.

White spruce (*Picea glauca* (Moench) Voss) is a shade tolerant conifer species that grows on upland soils across the boreal region of North America. In the Lake States, it occurs naturally as a component in mixed hardwood-aspen stands, but has been widely planted in monoculture plantations. In Minnesota alone, there are over 80,000 acres of white spruce plantations under 50 years of age (Miles et al. 1995). These plantations were often established based on the belief that white spruce suffers less severe impacts from spruce budworm (*Choristoneura fumiferana* Clemens) than the naturally occurring balsam fir (*Abies balsamea* (L.) Mill). However, ongoing outbreaks of this insect, particularly in older, dense plantations, have shown that white spruce is susceptible to budworm-induced top-kill and mortality (M. Albers and A. Jones, pers. comm.). This has left foresters a dilemma in how to manage these plantations when few management guidelines that incorporate spruce budworm in their recommendations. While markets have developed in recent years that allow foresters to thin dense and budworm-infested stands earlier, few management guides are available (e.g., Rauscher 1984) that help managers plan how these stands may respond in terms of growth and future suceptibility to budworm.

Density management diagrams (DMDs) are tools that can incorporate these concerns. These guides are based on the $^{-3}/_{2}$ power law of self-thinning that relates how mean plant size is inversely related to plant density (Dean and Jokela 1992, Smith and Woods 1997). While they cannot replace growth models, DMDs have distinct advantages over stocking charts. First, DMDs are largely independent of age and site quality (Dean and Joekela 1992). For example, when natural (i.e., unmanaged) stand development is plotted on the DMD (i.e., a stand trajectory), stands of the same initial density growing on high and low quality sites with follow the same size-density trajectory except that the stand growing on the higher quality site with move along the trajectory more quickly (the lack of a time component is also one of the major shortcomings of DMDs). Second, DMDs are widely applicable to predicting development of a broad range of forest resources or conditions that are influenced by stand density. Beyond the traditional uses like predicting diameter growth and stand volume, DMDs have been used as guides in the management for elk (*Cervus elaphus nelsonii*) and mule deer (*Odocoileus hemionus hemionus*) thermal and hiding cover (Smith and Long 1987), goshawk (*Accipiter gentilis*) nesting habitat (Lilieholm et al. 1993), and American martin (*Martes americana*) foraging habitat (Sturtevant et. al 1997). Basically, DMDs can be customized for management of any resource that varies with the structural attributes (i.e., size and density) of a forest stand. Third, DMDs can be developed for stands that are composed of multiple species (e.g., mixed northern hardwood-aspen stands) and accommodate the differential growth and mortality patterns of the species (e.g., Puettmann et al. 1992). Last, DMDs are empirically calibrated and ecologically based (Sturtevant et al. 1998); this can allow easier linkage to physiological and other ecological models. The mixed species DMD developed by Puettmann et al. (1992) could be linked easily to an interspecific competition model.

This paper presents a preliminary DMD for white spruce plantations in the Lake States. This work is part of a larger, long-term project that will refine this DMD to incorporate spruce budworm susceptibility and impact.

WHAT IS A DMD AND HOW IS IT DEVELOPED?

DMDs were introduced to North America in the late 1970s to help managers maximize timber production (Drew and Flewelling 1977, 1979), and became widely used throughout the western U.S. in the 1980s and 1990s (e.g., Smith and Long 1987, Dean and Jokela 1992, Smith and Woods 1997, Wilson et al. 1999). They relate a measure of plant size, commonly diameter at breast height or tree biomass, to plant density (Figure 1; Smith and Woods 1997). The size-density combinations are plotted on a graph with logarithmically transformed axes. According to the $^{-3}/_{2}$ power law of self-thinning, all stands plotted on logarithmic axes will fall below the maximum size-density (MSD) line (Line A in Figure 1). This line marks the upper boundary of size-density combinations and is determined by the density-dependent mortality within any stand (Smith and Woods 1997). If the plant size measure on the dependent axis is mean plant biomass, this theoretical line should have a slope of $^{-3}/_{2}$, although Puettmann (1990) provided several examples where this was not the case.

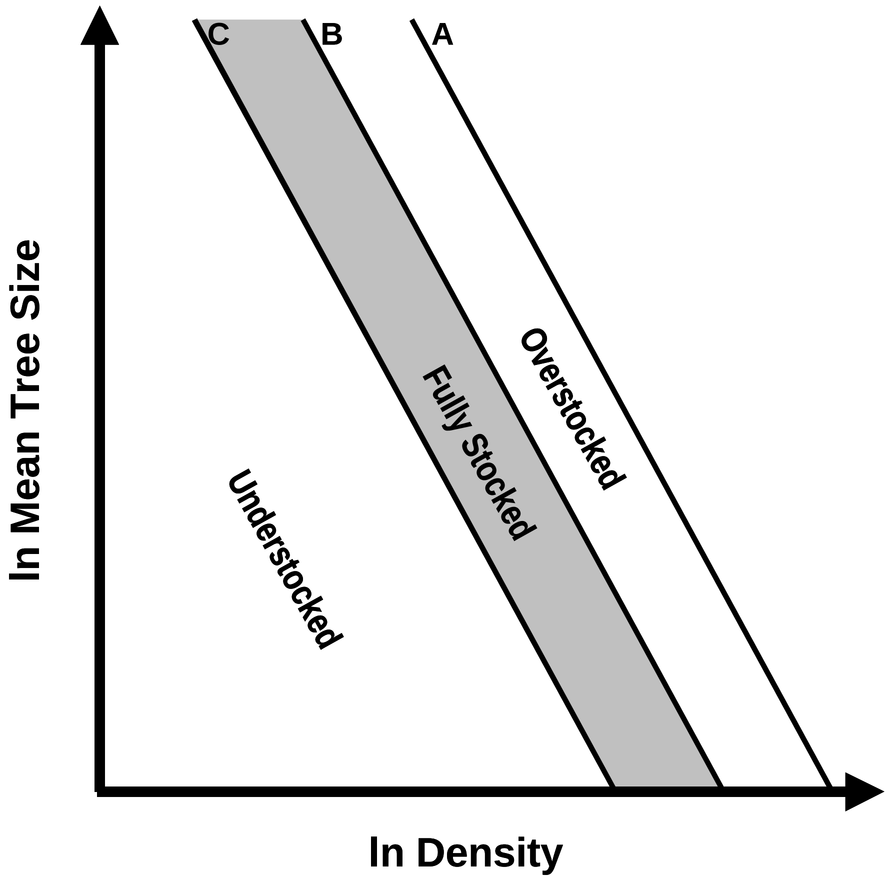

Figure 1. Example of density management diagram (DMD). The maximum size-density line (Line A) marks the uppermost boundary of density-dependent mortality; no stands will plot out above this line. The mortality initiation line (Line B) marks the point at which stands will begin to experience significant density dependent mortality. The maximum stand production initiation line (Line C) marks when stands begin to fully utilize the site. These three lines roughly demarcate zones of overstocked, fully stocked, and understocked stand conditions.

Beyond the maximum-size density line, a DMD usually displays other lines. All DMDs will have at least 2 additional parallel lines that fall below the MSD line (Figure 1). These lines are often theoretically based on the MSD line using relative densities[1]. The mortality initiation line (Line B in Figure 1; relative density = 0.55), defines when stands start to exhibit density-dependent mortality. When plotted, stands falling between this line and the MSD line are overstocked. The second, the maximum stand production initiation line (Line C in Figure 1; relative density = 0.40), marks the conditions at which trees fully occupy the site and the stand is highly productive. Stands falling below this line can be considered

[1]Relative density is the ratio of actual stand density to maximum stand density (as defined by the MSD line) for a given mean plant size. Therefore, the MSD has a relative density of 1.00.

understocked. Therefore, to maximize timber production, managers should maintain their stands between the maximum stand production initiation (Line C) and the mortality initiation lines (Line B) throughout most of the rotation. Another line typically found on DMDs is the crown closure (often at a relative density = 0.15). It should be noted that if sufficient data are available, authors have used regression techniques to determine both the slope and the placement (i.e. relative density) of each line (Puettmann 1990, Puettmann et al. 1993). Thus, authors use the theoretical relative densities for placement of the management lines only if data are lacking.

DMDs can have other variables superimposed onto the size-density axes. Often, if mean total tree volume is used for the dependent axis, authors will include isolines defining a mean diameter for trees. Additionally, some DMDs include isolines of mean tree height, stand volume per acre or hectare, and mean basal area (see Smith and Woods 1997). Furthermore, DMDs may include shaded areas that meet specific stand structure requirements for various management objectives (e.g., using diameter-crown relationships to characterize wildlife habitat quality as described in the introduction). These complex DMDs are often computerized, thereby allowing for quick assessments of differing management regimes.

HOW WAS THIS DMD DEVELOPED?

The white spruce DMD was developed using data from two sources. The largest dataset came from thinning experiments that the USFS-North Central Forest Research Station has been conducting over the past 30 years. This dataset includes 10 plantations in northern Minnesota, Wisconsin, and the upper peninsula of Michigan (G. Erickson, North Central Forest Research Station, Grand Rapids, MN, unpublished). The second dataset was provided by UPM-Kymmene Blandin Paper Company and includes one-time measurements of 12 plantations in northern Minnesota (C. Peterson, UPM-Kymmene Blandin Paper Company, unpublished). Only unthinned plots with white spruce proportions greater than 80% of total plot basal area (Smith and Woods 1997) were used in our analysis (n = 367 from 21 stands).

Placement of the maximum size-density (MSD) line is the first step in the development of a DMD. Following Smith and Woods (1997), we restricted the data to plots with densities greater than 400 trees per acre (tpa) and sorted the remaining plots into 0.05 ln density classes. Within each density class, plots with the maximum quadratic mean diameter were then used to fit to the following model:

$$\ln DBH_q = ß_o + ß_1 (\ln DEN),$$

where DBH_q = mean quadratic diameter at breast height in inches, and DEN = density of plot, expressed as trees per acre (tpa). The resulting model produced an "average" MSD line, i.e., fits a line that "on average" stands will approach and individual data points are distributed above and below it (Puettmann et. al 1993, Smith and Woods 1997). To find the "biological absolute" MSD line, the model was algebraically solved for $ß_o$ using the point with the largest positive residual. This following model is the true MSD line (Line A) that represents the absolute maximum plot DBH_q attained for any given density (Figure 2), i.e., no stands were found that had a higher mean diameter for a given density:

$$\ln DBH_q = 5.191 – 0.471 (\ln DEN).$$

The second step of DMD development is placement of the mortality initiation (Line B) and the maximum stand production initiation (Line C) lines. Although several recent DMDs

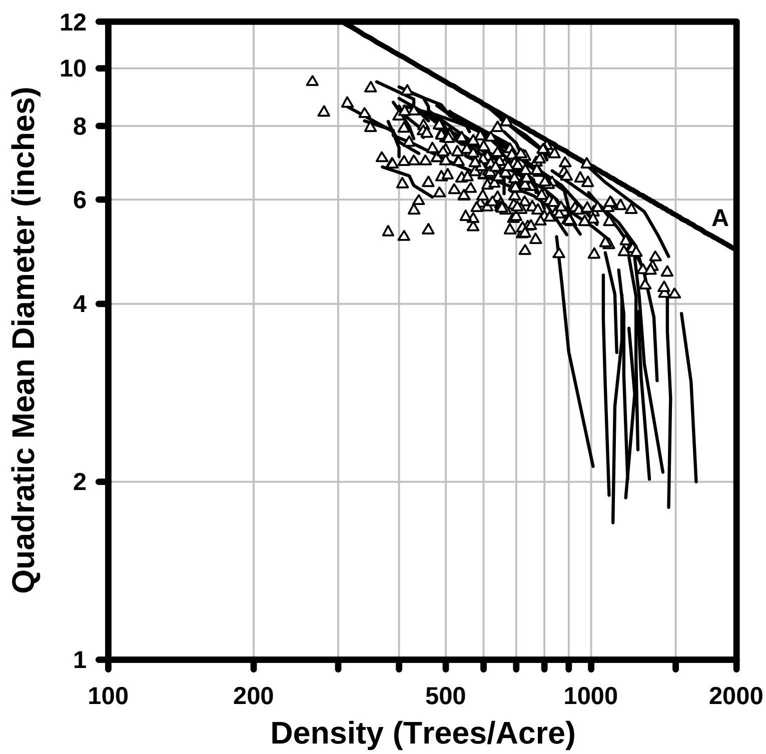

Figure 2. Plot development trajectories (solid lines) and individual plot measurements (triangles) of data used to develop the preliminary white spruce density management diagram (DMD) for the Lake States. The maximum size-density line (Line A) of this DMD has a slope of –0.473.

have statistically determined the slopes and intercepts for these lines (see Puettmann 1990), our dataset was not adequate to do so. Therefore, these lines were placed algebraically using the theoretical estimates of relative density of 0.55 and 0.40 for the mortality initiation (Line B) and maximum stand production (Line C) lines, respectively. The remaining line, the crown closure line (Line D), was developed from crown width equations provided by Ek (1974). The resulting DMD is shown in Figure 3.

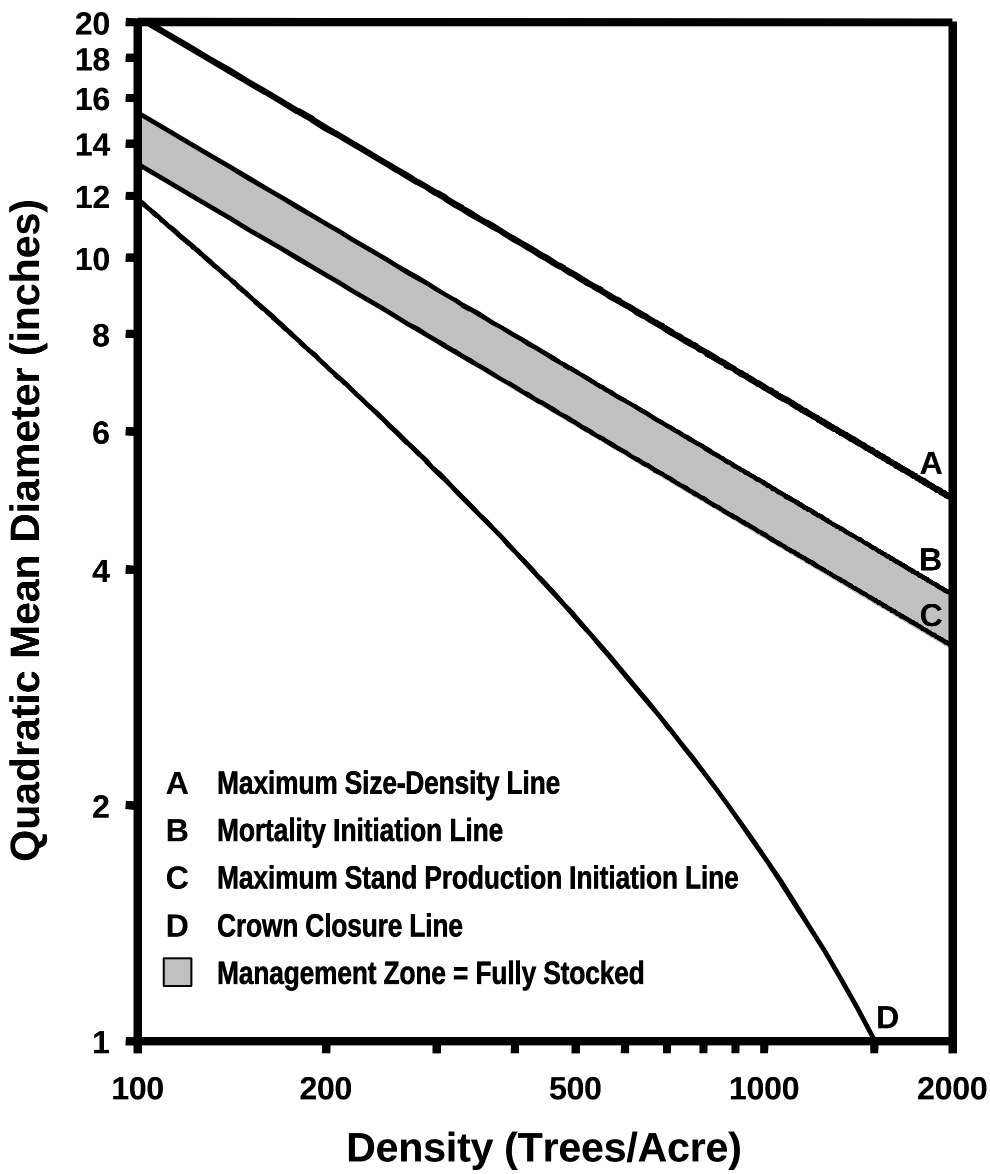

Figure 3. Preliminary density management diagram (DMD) for white spruce in the Lake States. Lines A-C all have slopes of –0.473 and have relative densities of 1.00, 0.55, and 0.40, respectively. Line D was derived from Ek (1974).

HOW DO I USE THIS DMD?

$\overline{\text{DBH}}$ vs. DBH_q

The proper use of this DMD requires understanding the difference between the arithmetic mean diameter ($\overline{\text{DBH}}$) and the quadratic mean diameter (DBH_q). Although both are a measure of an average diameter at breast height for the stand, they are calculated differently. $\overline{\text{DBH}}$ is the arithmetic average of diameters at breast height of a plot or stand., whereas DBH_q is the diameter at breast height of the tree with the mean basal area in a stand. It is calculated using the following formula:

$$\text{DBH}_q = 24\sqrt{\frac{\overline{\text{BA}}}{p \bullet \text{TPA}}},$$

where $\overline{\text{BA}}$ is mean basal area/acre and TPA is trees per acre. DBH_q is not influenced as greatly by outliers, i.e., extremly large or extremly small trees in a plot. In practical terms, for plantations DBH_q is usually just slightly greater than $\overline{\text{DBH}}$ by 0.1 to 0.5 inches, and $\overline{\text{DBH}}$ can be substituted for DBH_q. However, if there is a large difference in size between the largest and smallest trees in a stand, as would be in a multi-aged plantation, then the above assumption would not be accurate and DBH_q should be calculated.

Stand trajectories of unmanaged stands

In Figure 4, Stand I and II represent stands with different initial densities that were never thinned. Generally, unthinned plantations follow one of two trajectories, depending on the setup of the DMD. When minimum size (i.e., breast height or a minimum DBH) is used in stand calculations, ingrowth will take place. In this case, plantations will track to the right quickly and then vertically to the maximum stand production line (Line C), move nearly vertically to the mortality initiation line (Line B), and then move to the left and approach the MSD line (Line A) asymptotically as shown with Stand I. If ingrowth is negletiable (e.g., when using initial planting density, with plant biomass as the dependent variable, and/or the

DMD does not include small independent axis values), a plantation will track nearly vertically to Line B and then move to the left and approach Line A asymtopically as shown by Stand II.

There are a few details concerning stand trajectories that a user should consider. First, stands generally track much more slowly as competition intensifies, i.e., stands approach the MSD

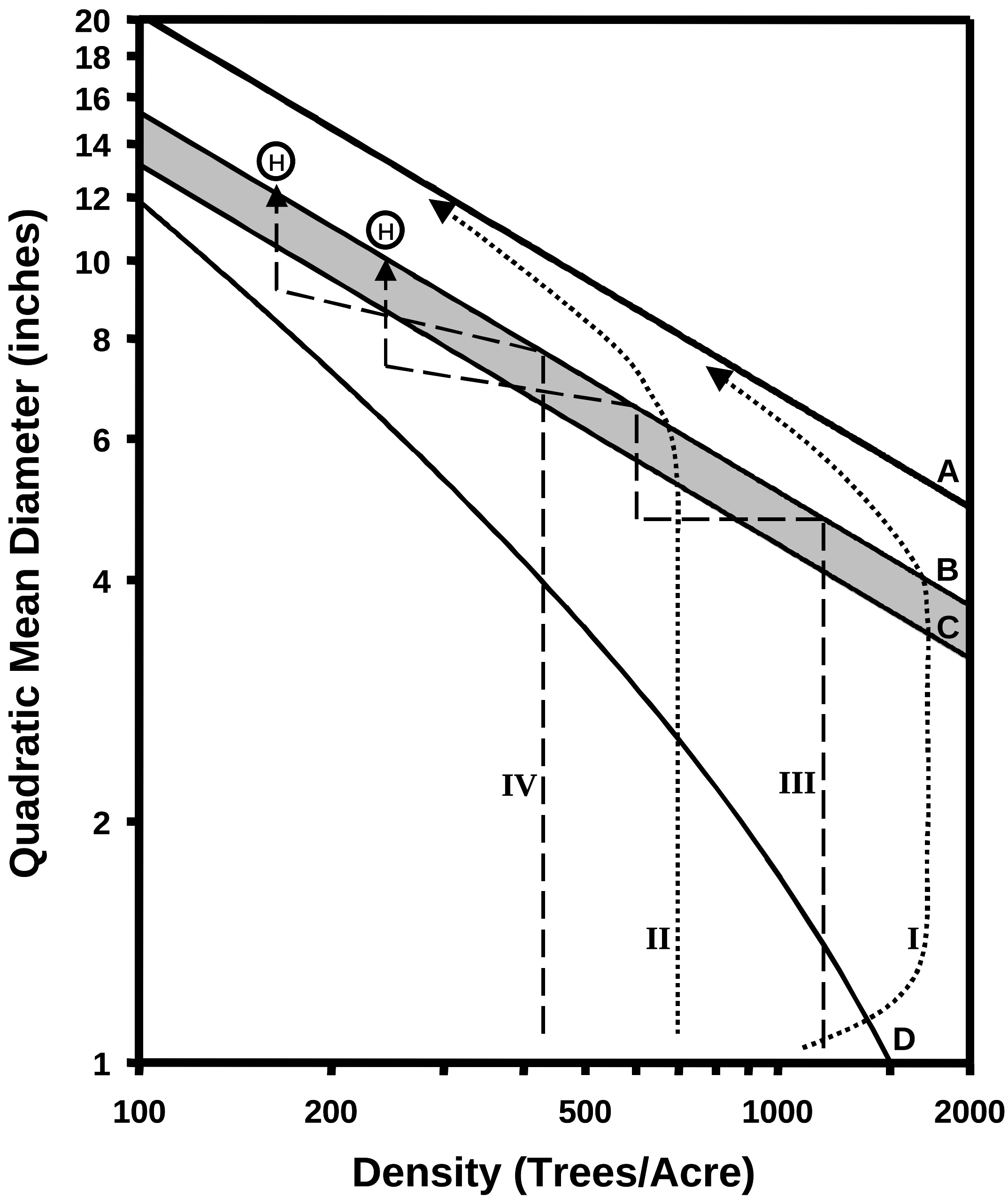

Figure 4. Stand trajectories for two unmanaged stands (dotted lines I and II) and two managed stands (dashed lines III and IV) with different initial densities. Only Stand I assume ingrowth. The various stand trajectories (I-IV) are discussed in the text. Final harvest for Stands III and IV are marked with a circled “H” on the diagram.

line on the DMD. For example, the time that it takes a stand to move from some arbitrary point to Line C will almost always be shorter than it takes to move that same distance above Line B. Therefore, if managers have a minimum diameter that they want the average tree to achieve in the shortest period of time, they better maintain the stand below Line B as long as possible. Second, plantations on higher quality sites will track almost identically to stands on lower quality sites, given the same planting density, but the higher quality sites will develop more quickly. Therefore, managers need to plan thinning activities earlier on high quality sites than on lower quality sites if they wish to maintain stands within the management zone (= fully stocked) of the DMD.

Using the DMD for management decisions

For the first example, assume a landowner manages a stand predominately for pulpwood and can afford some intermediate entries before final harvest. Stand III was planted at an initial spacing of 6' X 6' (1210 tpa). At 1210 tpa, this stand grew to a mean diameter of about 5 inches before substantial mortality occurred. At this time, a geometric thinning (shown by the flat horizontal line in the stand trajectory) reduced densities to 600 tpa, by removing every other row. This allowed the stand to develop to a mean diameter of approximately 7 inches before significant mortality occurred. The stand was thinned again, but this time using a commercial thinning from below. Because thinning from below removed the smallest trees, the DBH_q increased slightly (see increasing slope on Figure 4). At 250 tpa, the stand grew to a final mean harvest diameter of about 10 inches. This regime maintained tree growth and vigor throughout the rotation and allowed the landowner to capture significant pulpwood volume that would otherwise have been lost to mortality. In addition, the two thinnings allowed for selection of the highest quality crop trees.

Now for the second example, assume that the landowner emphasizes sawtimber production but only plans one commercial thinning before final harvest. Stand IV was planted at an initial spacing of 10' X 10'. At 440 tpa, the stand developed to a mean diameter of nearly 9 inches before significant mortality occurred. At this time an intense thinning from below reduces densities to 175 tpa, thereby allowing the stand to develop to an mean diameter of 13 to 14 inches before final harvest.

In these examples, losses in stand volume from mortality were minimized with thinning and harvesting before the stands were significantly above Line B. If more mortality were acceptable (e.g., to produce snags or downed woody debris), managers might choose to let the stand develop further beyond Line B. The dominant trees would still grow, albeit more slowly, and stand volume would continue to increase. However, if managers waited too long (i.e., let the stand development approach the A line), taper of the remaining trees would decline as the crowns became shorter. This would prohibit intense thins, as seen in Stand IV, since trees would be more prone to windthrow. Likewise, in both examples, we thinned to levels much below Line C. For some species, like red alder, when stands were thinned heavily from extremely high densities to densities far below Line C, this resulted in reduced height growth (Hibbs et al. 1989). In any case, thinning below Line C will lead to longer crowns as stems will not self-prune as quickly (Puettmann et al. 1993). However, vigor and diameter growth of individual trees will be increased and these intense thinnings reduce the number of entries required for a stand to reach a target mean diameter. Therefore, one should recognize that Lines B and C are approximate boundaries of the management zone; economic and nontimber constraints often make maintaining stands strictly within the management zone infeasible.

FINAL COMMENTS

This density management diagram is preliminary in nature. It was developed using a limited dataset that does not cover the full ranges of sizes and densities that white spruce plantations are grown at. Furthermore, this diagram was developed using only plantation records; using this diagram for natural spruce stands should be done with caution. Work is underway to expand the dataset and refine the slopes and intercepts of all lines.

Lastly, DMDs can only account for event and processes that are density-related (Puettmann et al. 1993). Research is ongoing to identify the effect that spruce budworm may have on this diagram. S. Seybold and D. Blackford (Department of Entomology, University of Minnesota) are involved in a multi-site, long-term thinning study of white spruce throughout Minnesota that will investigate growth of white spruce under a variety of budworm infestation levels and the impact of thinnings on spruce budworm populations. The end result may be a DMD that includes management zones that reduce spruce budworm populations, i.e. spruce budworm infestation probabilities. It may also include lines adjusted for stands that have experienced or are experiencing significant growth loss or mortality due to spruce budworm infestations.

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APPENDIX A: BLANK DMD

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