STOCKING EQUATIONS FOR REGENERATION IN MIXED OAK STANDS

Songlin Fei, Kim C. Steiner, and James C. Finley[1]

Abstract—Regeneration stocking equations for mixed-oak stands were developed based on data collected from nearly 14,000 plots in the central Appalachians. Maximum stand density was identified by plotting aggregate height against number of seedlings per plot, and was used as the reference level of the average maximum stand density (100 percent stocking or A-level stocking). Minimum stand density (B-level stocking) was estimated using the crown area and seedling height relationship of open-grown seedlings. Stocking equations were developed separately for plots having average seedling height below and above 9 feet. The resulting stocking equations provide an objective basis for evaluating stocking of young regeneration in the upland mixed-oak forest.

INTRODUCTION

Appropriate stocking equations or stocking charts, which serve as measures of stand density, have long been sought by foresters. Stocking can be measured using numbers of trees, quadratic mean diameter, mean volume, dominant height, or other stand properties appropriate to the concept of density (quantity per unit area). All stocking guides share one common concept – relative density. Relative density is the ratio of absolute density to a reference level. Measures of relative density assess crowding in forest stands by comparing the growing space available per tree with the growing space available to trees of the same size at some reference level of density (Stout and Larson 1988). Generally, the two major approaches to measure stocking are typified by: Reineke's (1933) stand density index (SDI) and Gingrich's (1967) stocking diagram. Most stocking charts, diagrams, and monographs are suitable only for bigger trees (> 12 feet in height or > 1 inch in dbh), and older stands (> 20 years). No stocking guide exists for seedlings or young stands for the upland mixed-oak forest. The seedling stage is very important because it determines the future stand structure. Failure to obtain adequate stocking of desired species can leave a stand unproductive for many years. Hence, developing a stocking guide for the regeneration stage is necessary and pressing, and that was the objective of this study.

SOURCE OF DATA

Three sets of data were used in this study. The first data set was collected in 52 mixed-oak stands in Pennsylvania. Depending on stand size, 15 to 30 permanent center points were systematically installed in a square grid on each stand. Four permanent sample plots with a radius of 3.72 feet (0.001-acre) were established around the center points at each cardinal direction at a distance of 16.5 feet. On each plot, all tree seedlings regardless of origin were recorded by species and height class and seedling cover percentage (i.e. percentage of plot area covered by seedling canopy) was estimated. All stands were measured approximately one year before harvest, 33 stands were re-measured one year after harvest, 16 stands were re-measured four years after harvest, eight stands were re-measured five years after harvest, and four stands were re-measured six years after harvest.

Data from 15 mixed-oak stands with stand ages of 6-12 years were also included in this study. The overstory of each of the 15 stands was removed 6-12 years prior the time of assessment, and the stand regenerated successfully after harvest. These stands were intentionally chosen to represent crown-closure or near crown-closure conditions. Depending on the size of the stand, 15 to 40 plots with a radius of 7.44 feet (0.004 acre plots) were sampled throughout the stands. In total, 504 plots were included in this data set. On each plot, all seedlings or saplings regardless of their origin were recorded by species and height, and percentage of crown cover was estimated.

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The final data set provided information for open-grown trees. Based upon abundance and availability, 567 open-grown trees that included the six major regeneration species in this region were measured in this data set: 81 red maples (*Acer rubrum* L.), 97 black birches (*Betula lenta* L.), 38 blackgums (*Nyssa sylvatica* Marsh), 92 white oaks (*Quercus alba* L.), 125 chestnut oaks (*Q. montana* Willd.), and 134 northern red oaks (*Q. rubra* L.). All selected trees had no competing neighbors at the time of measurement, and they were measured in stands that provided data for the 1st and 2nd data set. For each tree, species, height, stem dbh, and crown diameter were recorded. In order to have best crown size estimation, crown diameters were measured in four directions: longest dimension of the crown, and 45, 90, and 135 degrees off the longest dimension through the center.

DEVELOPMENT OF STOCKING GUIDES

Average Maximum Density

Plots from the first two data sets that had at least one seedling were utilized to identify plots that were experiencing the maximum level of competition. Aggregate height (Fei and others), a composite measure of stand density, was calculated on each plot and then plotted against seedling density on a log-log scale (fig. 1). Two clear boundaries are apparent. The lower boundary is the minimum plot aggregate height for a given number of seedlings. It represents plots covered only with seedlings of the smallest height (one inch in this study). The upper boundary corresponds to the observed maximum aggregate heights over the range of observed seedling densities. To ensure that the observed maximum aggregate height represents the biological average maximum level of competition or the ecological maximum carrying capacity, plots around the upper boundary were further examined. Figure 1 was divided into 0.05 unit width slices along the x-axis, and the top two plots near the upper boundary in each slice were then selected. For all selected plots, percentage of seedling cover was further checked, and plots with less than 90 percent seedling cover (by measurement) were eliminated. The remaining selected plots were the ones chosen to represent the biological frontier. In total, 110 plots were used to define the biological frontier. Maximum aggregate

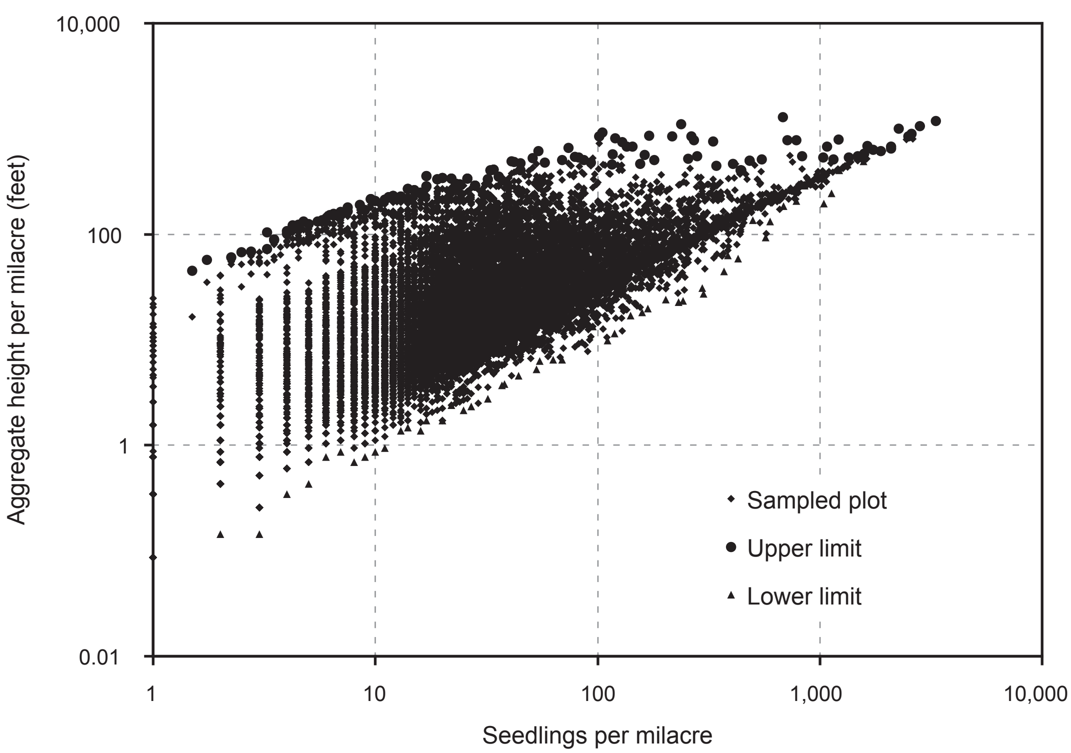

Figure 1—Relationships between aggregate height and number of seedlings per milacre on 13,853 surveyed plots. Plots with maximum or minimum aggregate height at a given density are highlighted.

height increases as seedling density increases. But the increase is progressively smaller as the number of seedlings per milacre increases. The upper and lower boundaries converge as seedling density approaches the maximum.

As with Gingrich's (1967) stocking guide and Reineke's (1933) SDI, average maximum competition was selected to serve as the reference level to develop regeneration stocking equations. To develop stocking equation, we first analyzed relationship between average crown area and height for seedlings experiencing the average maximum level of competition (seedlings in the 110 biological frontier plots). Crown area was determined simply by dividing plot size by the total number of seedlings in these frontier plots. Regression analysis was then carried out by using crown area as the dependent variable and average seedling height as the independent variable. Since the relationship between crown area and seedling height has a significant shift for seedlings above and below 9 feet tall on average (Fei 2004), two different regression lines were fitted to represent the two different crown area-height relationships. Using the crown area-height relationship, the stocking level on a plot then can be calculated as follows if seedling height is measured in feet:

$$\begin{aligned} S &= [(N \bullet 0.0682 \bullet AvgHt^{\,1.0032}) / (m \bullet 43560)] \bullet 100 \\ &= (0.00016/m) \bullet N \bullet AvgHt^{\,1.0032} \\ &= (0.00016/m) \bullet N \bullet (\Sigma h_i / N)^{1.0032} \qquad (AvgHt < 9 \text{ feet}) \end{aligned} \tag{1}$$

$$\begin{aligned} S &= [(N \bullet 0.0044 \bullet AvgHt^{\,2.3667}) / (m \bullet 43560)] \bullet 100 \\ &= (0.00001/m) \bullet N \bullet AvgHt^{\,2.3667} \\ &= (0.00001/m) \bullet N \bullet (\Sigma h_i / N)^{2.3667} \qquad (AvgHt \geq 9 \text{ feet}) \end{aligned} \tag{2}$$

where

S = percentage of School of Forest Resources, regeneration stocking
N = the total number of seedlings per plot
$AvgHt$ = the average height of all seedlings
m = the size of plot in acres
h_i = height of seedlings on the sampled plot (i = 1, ……, N)

Average Minimum Density

Average minimum stand density at full canopy closure, or Gingrich's (1967) B-level stocking, represents an ideal condition in which a stand is fully covered with seedlings with maximum crown area and no inter-seedling competition. Crown areas of open-grown seedlings were used to define the maximum crown area. Crown area of open-grown seedling was calculated using average crown diameters from field measurement. To compute the minimum density at a given average seedling height, the relationship between crown area and seedling height of open-grown seedlings was used.

Regression analyses of crown diameter against seedling height were performed by species. Comparisons of regression coefficients among different species indicated that the overall relationship between crown diameter and seedling height is not significantly different among species, although crown diameter of oak species was slightly greater than non-oak species when seedling heights are small (fig. 2). Consequently, the same crown area-diameter relationship was used for the six major regeneration species. Minimum number of seedlings with maximum crown area that can fully cover a plot can then be calculated by dividing total plot area with average maximum crown area of seedlings at given average height. Since the relationship between crown area and seedling height also has a significant shift for open-grown seedlings above and below 7 feet tall on average (Fei 2004). Two different equations were developed for seedlings < 7 feet tall and for seedlings ≥ 7 feet tall:

$$N = (43560 \cdot m) / (0.4051 \cdot AvgHt^{1.50}) = 107529 \cdot m / AvgHt^{1.50} \qquad (AvgHt < 7 \text{ feet}) \tag{3}$$

$$N = (43560 \cdot m) / (0.0479 \cdot AvgHt^{2.55}) = 909395 \cdot m / AvgHt^{2.55} \qquad (AvgHt < 7 \text{ feet}) \tag{4}$$

where

N = the minimum number of seedlings per plot
m = the size of plot in acres
$AvgHt$ = the average height of seedlings

Because less than 10 open-grown seedlings with height smaller than one foot were measured, the minimum number-height relationship for small size seedlings is not as robust as for larger seedlings.

DISCUSSION

Regeneration equations developed above have reasonable quantitative connections with the former stocking guides. For instance, if there is only one tree with minimum crown area (A-level) on a milacre plot and the plot is fully stocked, then the height of the tree must be ≥ 49 feet based on the regeneration stocking equation. Using the highly deterministic height-diameter relationship of trees in the upper-limit plots (*Height* = 8.79*dbh* + 6.69, $r^2 = 0.83$), the correspondence tree must have a dbh ≥ 4.8 inches. With the same scenario, Gingrich's (1967) equation predicts a minimum dbh of 4.0 inches for oak and hickory species; McGill's (1999) equation predicts a minimum dbh of 4.7 inches for northern red oak; while Stout's (1988) equations predict a minimum dbh of 4.5 inches for red maple. In an alternative scenario, if there is only one tree with maximum crown area (B level) on a milacre plot and the plot is fully stocked, then the height of the tree must be ≥ 15 feet based on the resulting regeneration stocking, and the correspondence tree must have a dbh ≥ 1.7 inches by the height-diameter relationship of open-grown

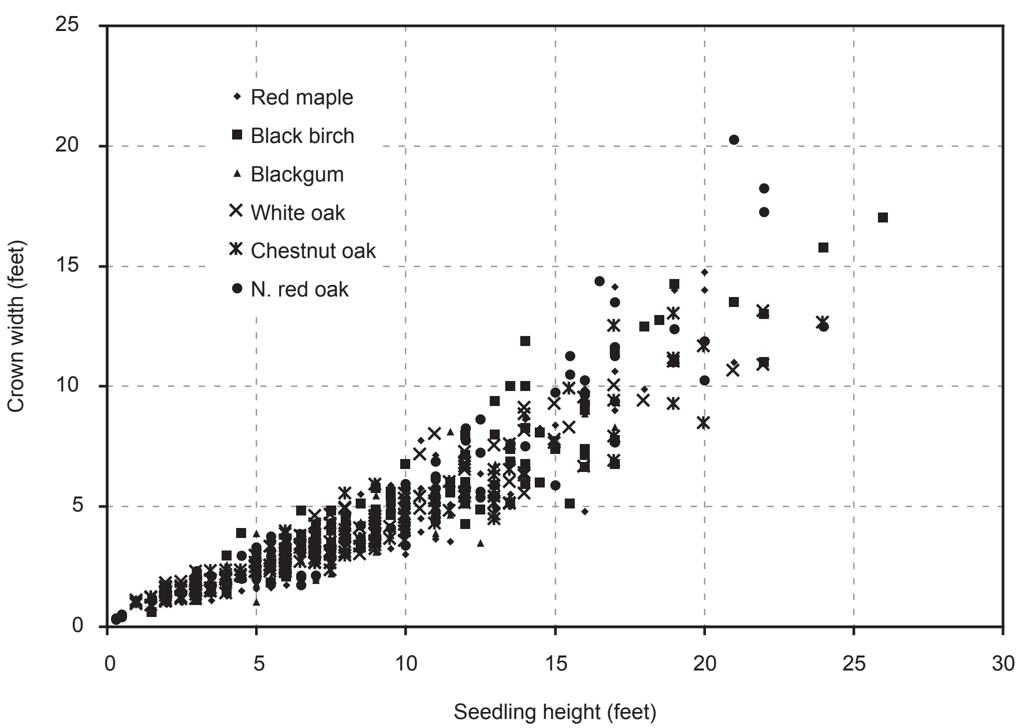

Figure 2—Relationship between crown diameter and seedling height by species for open-grown seedlings and small saplings.

trees ($Height = -0.90dbh^2 + 7.82dbh + 4.18$, $r^2 = 0.87$). Based on Gingrich's and McGill's equations, the minimum dbhs in the second scenario are 2.3, 1.6 inches, respectively. Both scenarios indicate a good connection between the regeneration stocking and other stocking guides for mature stands.

The use of the regeneration stocking equations is rather simple. The equations can be used both in pre- and post-harvest situations. For example, if a milacre plot has 100 seedlings with average height of three feet, we can plug these parameters in equation (1) and calculate the stocking value, which is about 50 percent. By plugging these parameters in equation (3), we can determine that we need 21 seedlings with average height of three feet to reach the B-level stocking. Hence, this plot will eventually reach full stocking if no major disturbances occur. Forest manager can use the stocking value to determine if the current stocking is adequate for their management goal. The resulting regeneration stocking equations provide an acceptable and objective basis for evaluating stocking of tree regeneration in the upland mixed-oak forest. We suggest other researchers explore the use of the stocking equations for describing and assessing regeneration stocking.

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