STAND DENSITY INDEX AS A TOOL TO ASSESS THE MAXIMIZATION OF FOREST CARBON AND BIOMASS

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ABSTRACT

Given the ability of forests to mitigate greenhouse gas emissions and provide feedstocks to energy utilities, there is an emerging need to assess forest biomass/carbon accretion opportunities over large areas. Techniques for objectively quantifying stand stocking of biomass/carbon are lacking for large areas given the complexity of tree species composition in the U.S. Relative density, as determined through the Stand Density Index, may provide a technique to rapidly assess stand biomass/carbon stocking across the entire U.S. Using this approach in the eastern U.S. for 24 of the most common tree species, we found that maximum live aboveground tree carbon decreased as tree interspecific stocking decreased (i.e., toward more pure forest stands); this result was more pronounced in overstocked stands. Although the relative approach detailed in this study may not be appropriate at local scales for intensively managed forest types, it would be useful for making informed policy decisions at large scales where complex stocking and tree species mixtures complicate carbon/biomass studies. We suggest that future studies explore refinement of the maximum SDI model for national applications in the carbon/biomass arena.

INTRODUCTION

Forests and their products play a critical role in the carbon (C) cycle by reducing atmospheric levels of CO_2 and other greenhouse gases through emission avoidance and reduction of atmospheric levels (Malmsheimer and others 2008, Ryan and others 2010). In particular, forests may prevent C emissions through wood substitution (e.g., wood instead of concrete for construction), biomass substitution (e.g., biomass fuels for energy instead of fossil fuels), wildfire behavior modification (e.g., biomass removal before wildfire emissions), and avoided land-use change (e.g., deforestation). In addition, forests can reduce atmospheric concentrations of C through sequestration (e.g., increasing ecosystem C storage through standing live-tree growth) and C storage in wood products (e.g., C stored in lumber and furniture) (Ryan and others 2010). Given the ability of forests to mitigate C atmospheric concentrations, there is a growing need to evaluate the effects of various forest management practices on C budgets (Lindner and others 2008, Malmsheimer and others 2008). Recently, forest management strategies for maximizing forest volume or biomass have been applied to the maximization of C sequestration (e.g., even-aged, single-species plantations; Jacobs and others 2009). The increased application of forest management for maximizing aboveground C storage will likely encounter a novel array of tree species compositions and stand densities. Basic tenets of tree species diversity and biomass stocking attributes would greatly aid efforts to estimate the effects that various management activities would have on maximizing aboveground C storage.

A major hurdle to assessing C storage opportunities is accurately quantifying the biomass/carbon stocking of individual stands, especially given the diversity of forest species compositions across the U.S. Stocking may be defined as the number of trees per unit area currently in a stand relative to the maximum potential possible The relative density (RD) of live trees in any given forest may be defined as a function of Stand Density Index (SDI) and maximum SDI. SDI was first proposed by Reineke (1933) as a stand density assessment tool based on size-density relationships observed in fully stocked pure or nearly pure stands. A metric version of SDI is defined as the equivalent trees per hectare at a quadratic mean diameter of 25 cm and is formulated as:

$$SDI = tph\ (DBH_q/25)^{1.6} \qquad (1)$$

where tph is number of trees per hectare, and DBH_q is quadratic mean diameter (cm) at breast height (d.b.h.; 1.4 m) (Long 1985). One way to appropriately determine SDI in stands with non-Gaussian diameter distributions is to determine the SDI for individual d.b.h. classes and then add them for the entire stand (Long and Daniel 1990). This methodology (Shaw 2000, Ducey and Larson 2003) is formulated as:

$$SDI = \Sigma\ tph_i\ (DBH_i/25)^{1.6} \qquad (2)$$

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where DBH_i is the midpoint of the i^{th} diameter class (cm) and tph_i is the number of trees per hectare in the i^{th} diameter class (Shaw 2000).

To determine a stand's RD, the SDI of the stand is typically compared to an empirically observed, species-specific maximum SDI. This process is straightforward in monocultures, but confounded in mixed-species stands. To overcome this limitation, Woodall and others (2005) proposed a methodology to estimate stand-specific maximum SDI regardless of species mixture by using the mean specific gravity of all trees in the stand to estimate a stand's maximum SDI (SDI_{max}):

$$E(SDI_{Max})= b_o+b_1(SG_m)+e \qquad (3)$$

where E() is statistical expectation and SG_m is the mean specific gravity for all trees in each plot. The higher the specific gravity of a species, the higher its modulus of elasticity within its bole, the more foliage that can be supported in its crown, and the fewer trees per unit area needed to support a site-limited amount of leaf area (Dean and Baldwin 1996). By using the summation method (Shaw 2000) to determine the current SDI of a stand and the Woodall and others (2005) model to predict a maximum SDI (based on the mean specific gravity of all tree species in the plot), we can determine the RD of a given plot by dividing current SDI by potential maximum SDI. With the ability to estimate the biomass stocking of any given forest stand regardless of species diversity, the goal of this study was to assess how 99^{th} percentiles of standing live and dead tree aboveground C storage relate to stand relative density (RD) and levels of interspecific stocking in the eastern U.S.

METHODS

The Forest Inventory and Analysis (FIA) programof the USDA Forest Service is the primary source for information about the extent, condition, status, and trends of forest resources in the United States (Smith et al. 2009). FIA applies a nationally consistent sampling protocol using a quasi-systematic design covering all ownerships in the entire nation (national sample intensity is one plot per 2,428 ha) (Bechtold and Patterson 2005). Land area is stratified using aerial photography or classified satellite imagery to increase the precision of estimates using stratified estimation. Remotely sensed data may also be used to determine if plot locations have forest land cover; forest land is defined as at least 0.4 ha in size, at least 36.6 m wide, and at least 10 percent stocked with tree species (Bechtold and Patterson 2005). FIA inventory plots established in forested conditions consist of four 7.2-m fixed-radius subplots spaced 36.6 m apart in a triangular arrangement with one subplot in the center (USDA Forest Service 2007). All trees (standing live and dead) with a d.b.h. of at least 12.7 cm are inventoried on forested subplots. Within each subplot, a 2.07-m microplot offset 3.66 m from subplot center is established where all live trees with a d.b.h. between 2.5 and 12.7 cm are inventoried. All subplots within the same forest condition (e.g., forest type or stand age) were combined for areal estimates of tree attributes at the hectare level (study plot).

All inventory data are managed in a publicly available FIA database. Data for this study were taken entirely from the FIA database using the most recent annual inventory in 30 eastern states for a total of 72,025 unique observations. The associated field data are available for download at the following site: http://fiatools.fs.fed.us (FIA Datamart). Annual inventories for each state were first initiated between 2000 and 2003 and run through 2008, and sample intensities may vary by state. The 24 most common tree species in terms of total live tree aboveground gross cubic foot volume were selected as focus study species. For computing stand attributes such as density and species composition, all tree species were considered on each study plot. Interspecific stocking was assessed by comparing the RD of each study species on each plot to RD of the plot (species composition purity ratio, SCP). For example, if a plot is 100 percent stocked with white oak (*Quercus alba* L.), then its stand RD and white oak SCP ratio would be 1.0. By contrast, if it is 100 percent stocked, but only 10 percent of the stand is stocked with white oak and 90 percent of the other stocking is occupied by other species, then its plot RD would be 1.0 and its white oak SCP ratio would be 0.1. The 99th percentile live aboveground tree C stocks (LAGC) and standing dead tree C stocks (DAGC) stocks were calculated for a matrix of stand stocking and SCP ratios: three classes of stand stocking (under-stocked, 0.0-0.3 RD; well-stocked, 0.3-0.6; over-stocked, 0.6+) and 10 classes of SCP ratios (0.1 intervals).

RESULTS AND DISCUSSION

Across all study species, means of the 99^{th} percentile LAGC ranged from 40 to 50 Mg/ha, 70 to 105 Mg/ha, and 110 to 165 Mg/ha, for under-, well-, and over-stocked stands, respectively (Fig. 1a). Overall, as stand stocking increased, the average 99^{th} percentile of LAGC for all study species decreased with increasing stand purity (increasing SCP ratios) along with a difference in the average 99^{th} percentile LAGC between classes of stand stocking. In contrast, as stand stocking increased, the 99^{th} percentile of DAGC decreased with increasing stand purity (increasing SCP ratios); however, there was no difference in the average 99^{th} percentile DAGC between classes of stand stocking (Fig. 1b). The mean 99^{th} percentile of DAGC across all study species ranged from 20 to 27 Mg/ha when the SCP ratio was 0.3 compared to a range of 7 to 14 Mg/ha when the SCP ratio was above 0.7.

The trends in 99th percentiles of LAGC indicate that, for many tree species assemblages, increasing tree species diversity might increase maximum LAGC storage. This relationship between maximum LAGC and species has important implications for emerging objectives such as indentifying optimal species mixtures for forest management strategies aimed at providing carbon and biodiversity benefits (Paquette and Messier 2010). Based on the findings of previous work examining productivity within mixed-species stands, these benefits may be best achieved in stands composed of species with complementary characteristics (e.g., differences in shade tolerance and height growth rates; Kelty 2006).

A most promising finding was that RD may be rapidly determined for forest stands through use of SDI and maximum SDI models. In the context of opportunities to maximize C or biomass in forest stands, SDI provides a viable technique for quantitatively exploring numerous policy issues related to tree species diversity and C/biomass stocking potentials. We suggest that future studies explore the use of RD, as estimated through SDI and the maximum SDI model, as a tool in large-scale C/biomass studies. Furthermore, refinement of the maximum SDI model for national application, based on emerging work by Ducey and Knapp (2010), will be a critical step toward increasing the accuracy of future large-scale estimates.

CONCLUSIONS

RD, as determined through SDI and maximum SDI models, provides a quantitative technique to rapidly assess stand biomass/C stocking across the entire U.S. Although this approach may not be appropriate at local scales for intensively managed forest types, it is useful for making informed policy decisions at large scales where complex stocking and tree species mixtures complicate C/biomass studies. We found in this study that maximum LAGC decreased as tree interspecific stocking decreased (i.e., toward more pure forest stands), a result that was more pronounced in over-stocked stands. It is suggested that future studies explore refinement of the maximum SDI model for national applications in the biomass/C arena.

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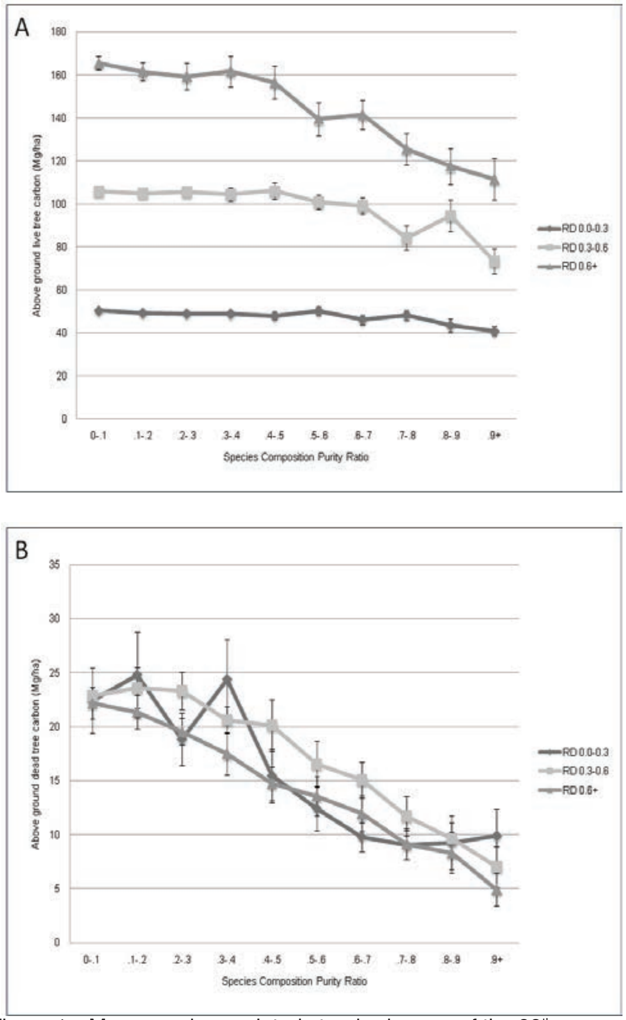

Figure 1—Means and associated standard errors of the 99th percentile aboveground live tree carbon for all study species for (a) standing live and (b) standing dead trees by 3 levels of stand stocking (under-, well-, over-stocked) and 10 levels of increasing species composition purity (stocking assessment based on relative density, RD).