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Short communication

# The relative density of forests in the United States

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**Abstract**

A relative stand density assessment technique, using the mean specific gravity of all trees in a stand to predict its maximum stand density index (SDI) and subsequently its relative stand density (current SDI divided by maximum SDI), was used to estimate the relative density of forests across the United States using a national-scale forest inventory. Live tree biomass (dry metric tons) varies widely across the US with the largest amounts in the Pacific Northwest region followed by the hardwood forests of the eastern US. In contrast, the range of relative density appears to be less disparate with numerous forests across the US having densities as high as areas in the Pacific Northwest. Overall, the large-scale assessment of relative density indicates that the majority of forests in the US are fully occupied in a rather contiguous pattern except for areas of the western US.


*Keywords:* Stand density index; Relative density; United States; Carbon; Fire

## 1. Introduction

Relative density (RD) is a quantification of the current density of a forest stand (e.g., basal area or stand density index) in comparison to some maximum level. Methods to determine RD have been almost entirely focused on individual stands at local or regional scales (for examples, see Reineke, 1933; Krajicek et al., 1961; Gingrich, 1967; Drew and Flewelling, 1979). However, the focus in recent years has shifted toward national-scale density assessments associated with fuel loading (for examples, see Keane et al., 2002; Schmidt et al., 2002; Vissage and Miles, 2003) and carbon stock analyses (for examples, see Smith and Heath, 2004; Smith et al., 2004a). In the case of carbon accretion, monitoring the current and potential impacts of forest management activities on greenhouse gas budgets is of critical importance (Smith et al., 2004a). Therefore, identifying US forests where stand growth may be stagnating or increasing aids efforts to predict future forest carbon stocks. Consequently, a need has emerged for objective techniques to broadly estimate the relative density of forests across the US.

Stand density index (SDI) has been proposed as a technique for estimating the RD of forests at large scales where uneven-aged and mixed species stands are typical (USDA, 2005; Woodall et al., 2005). SDI is a stand density assessment tool based on the size-density relationships observed in fully stocked pure or nearly pure stands (Reineke, 1933). A stand's maximum SDI is defined as the maximum density (trees per hectare) that can exist for a given mean tree size (25 cm) in a self-thinning population (Long, 1996). To determine RD, the SDI of any particular stand is compared to the maximum SDI characteristic of the stand's species composition. Recently, Woodall et al. (2005) proposed a methodology that estimates the maximum SDI for any stand, regardless of species composition. Briefly, Woodall et al. (2005) proposed using the mean specific gravity of all trees in a stand to estimate its unique maximum SDI. By using the summation method (Shaw, 2000) to determine the current density of a stand and the Woodall et al. (2005) model to predict a maximum SDI, we may determine the RD of stands across the US (current SDI/maximum SDI).

Given the importance of determining RD in national-scale forest assessments, applying new RD methodologies to a national inventory database for estimating current RD is highly warranted. Therefore, the objectives of this study are (1) to estimate the current standing live tree dry biomass and RD (current SDI/maximum SDI) for all plots in the national inventory database (2002 Resource Planning Act Database, RPADB), (2) to estimate total timberland area by class of RD for the US, and (3) to determine mean standing live tree dry biomass and RD (along with associated standard errors for RD) by Environmental Monitoring and Assessment Program (EMAP) hexagon for the US.

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## 2. Methods

### 2.1. Data

Individual plot data from the 2002 RPADB (Smith et al., 2004b) were used as observations in this study. The RPADB database contains plot and tree data predominantly collected by the USDA Forest Service's Forest Inventory and Analysis (FIA) program. Briefly, the plot design for FIA inventory plots consists of four 7.2-m fixed-radius subplots spaced 36.6 m apart in a triangular arrangement with one subplot in the center. All trees, with a diameter at breast height of at least 12.7 cm, are inventoried on forested subplots. The majority of plots in the RPADB consisted of FIA plots, while remaining plots were from National Forest System and Bureau of Land Management inventories. For further information on the RPADB and the FIA sample design, refer to Smith et al. (2004b) and Bechtold and Patterson (2005). The study dataset consisted of inventory plots that were at least partially forested (at least one part of any inventory plot had a forest condition present) from the RPADB (note: Alaska, Hawaii, and US territories were not included in the analysis due to lack of data). Furthermore, because the inventory plots typically consisted of spatially disparate subplots, plots were sometimes separated into separate observations based on forest conditions such as different forest types or stand conditions (clear-cut versus old-growth; for condition information see Bechtold and Patterson, 2005). The study dataset consisted of 127,851 inventory plots; which, due to differing forest conditions on individual plots, resulted in 135,104 observations.

### 2.2. Analysis

The total standing live tree dry biomass (metric tons/hectare), mean specific gravity for all trees, and SDI (summation method) were determined for each plot in the RPADB. The specific gravity for all study trees was based on data available from the USDA Forest Service's Forest Products Laboratory (USDA, 1999). For very rare tree species missing published specific gravity (SG) information, a default conifer and hardwood SG was used (USDA, 1999). The current SDI was determined for each plot by using the summation method:

$$\mathrm{SDI} = \sum \mathrm{tph}_i \left(\frac{\mathrm{DBH}_i}{25}\right)^{1.6} \quad (1)$$

where $\mathrm{DBH}_i$ is the midpoint of the $i$th diameter class (cm) and $\mathrm{tph}_i$ is the number of trees per hectare in the $i$th diameter class (Long and Daniel, 1990; Long, 1995; Shaw, 2000). To determine the RD of each plot, the maximum SDI for each plot was estimated using a maximum SDI model:

$$E(\mathrm{SDI}_{\max}) = 3546.7 - 3927.3(\mathrm{SG}_{\mathrm{m}}) \quad (2)$$

where $E(\cdot)$ is statistical expectation and $\mathrm{SG}_{\mathrm{m}}$ is the mean specific gravity for each study plot (Woodall et al., 2005). Maximum SDI model (Eq. (2)) parameter estimates are for estimating a 99th percentile maximum SDI. These parameter estimates were used in this study as surrogate estimates for the maximum SDI model because of their superior fit. RD was estimated by dividing the SDI by $\mathrm{SDI}_{\max}$ for each plot.

Each plot was assigned to an EMAP hexagon. EMAP is a map produced by the US Environmental Protection Agency (Overton et al., 1990; White et al., 1992) where a hexagonal (64,800 ha) array is superimposed across the US. Mean biomass and RD were computed for all the plots within each EMAP hexagon. Additionally, standard errors were computed for all mean RD's by EMAP hexagon. Up to 16 RPADB plots were located within each EMAP hexagon sometimes resulting in 20+ observations due to multiple forest conditions, while in sparsely forested regions of the US substantially less RPADB observations constituted the mean. For hexagons in which only one RPADB observation was present (9% of hexagons containing RPADB observations), the mean RD was the value of the single RPADB observation, while the standard error was null. In order to determine total forest areas by class of RD, forest area population estimators were applied to the RPADB plots (Smith et al., 2004b). In order to remove non-forest areas from EMAP hexagons, a non-forest mask using a classified National Land Cover Dataset (NLCD, Vogelmann et al., 2001) was used in all maps.

## 3. Results and discussion

Total standing live tree dry biomass varied as expected across the US (Fig. 1). The largest amounts of biomass are located in western Oregon and Washington, along with northwestern California. Moderate levels of biomass are located along the Appalachian Mountains, from northern Georgia into central Maine, encompassing much of the hardwood region of the US. The rest of the US is occupied by forests containing between 1 and 100 m/ha on average, with infrequent and possibly random locations of extremely heavy biomass accumulations (200+ m/ha). Although these findings are not unique, they are a crucial component to evaluating RDs and subsequent forest growth or thinning opportunities.

The RD of forests across the US varied in a pattern similar to standing live tree dry biomass (Fig. 2). RD was highest for forests in the Pacific Northwest and for hardwood forests of the Mid-Atlantic and Appalachian Mountains. Forest areas of the Rocky Mountains were also estimated as having a high RD; however, these areas are not as expansive and contiguous as the Pacific Northwest or eastern central hardwoods. Relative density measures, such as SDI, may underestimate RD in extremely arid areas where stockability may become an issue (for example, see Cochran et al., 1994). Therefore, forests in xeric western environments may have even higher RDs than estimated by this study. Forests estimated as having very low RDs broadly included eastern Oregon, southern Idaho, Minnesota, southern Wisconsin, lower Michigan, and the southeastern pine areas of Georgia, Alabama, Mississippi, and Louisiana. The range of RDs was smaller than the range of biomass estimates. Numerous areas of the US have high RDs equivalent to those of the Pacific Northwest: eastern hard-

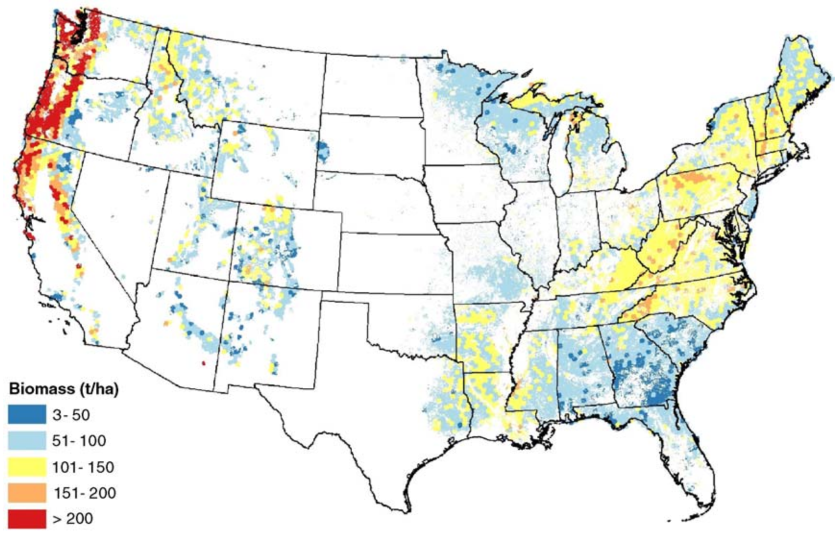


Fig. 1. Mean forest biomass (metric tons/hectare) of all RPA inventory observations by EMAP hexagon across the US.

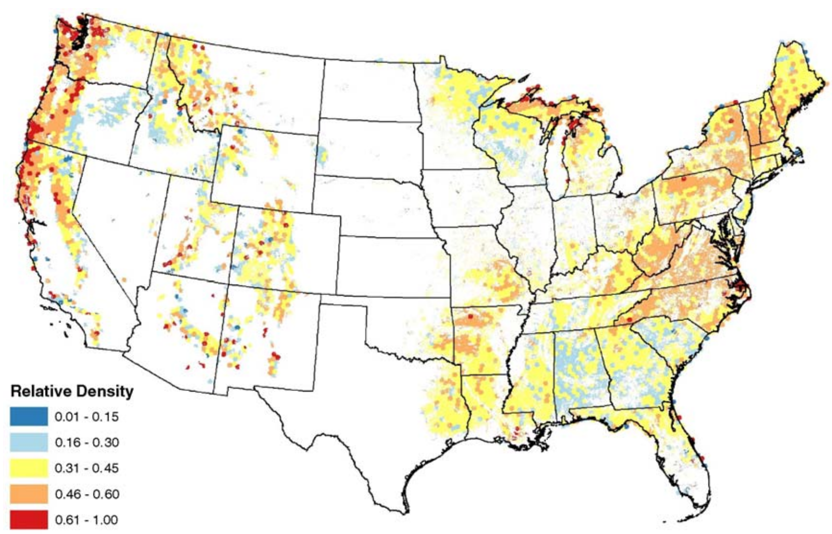


Fig. 2. Mean relative density of all RPA inventory observations by EMAP hexagon across the US.

woods; most forest areas of the Rockies; northern areas of Wisconsin and Michigan, hardwood forests of Missouri, Indiana, and Arkansas; and scattered coastal areas of the Carolinas. Because RD may be better correlated with a stand's current stage of development than its total biomass (Oliver and Larson, 1996), the distribution of RDs across the US is likely driven by regional and local forest stand disturbance and development events.

Population estimates indicate that over 80% of forests in the United States are below the limits of self-thinning (RD $> 0.6$), while over 68% of forests in the United States were at or above their lower limits of full site occupancy (RD $> 0.3$) (for interpretations of RD using the SDI technique see Long, 1985; Long and Daniel, 1990) (Table 1). In terms of timberland area, 131.1 million ha are fully occupied forests with only 20 million ha of that total being at risk from imminent mortality. Given the full site occupancy of the majority of forests in the US, together with slowing forestland area accretion (Smith et al., 2004b), the forests of the US may be broadly viewed as mature with little potential for the influx of younger and/or less occupied forests without widespread disturbance, mortality, or accumulation of new forestland.

Table 1
Total forest area (hectares) and percentage of total forest area by classes of RD for the United States

| Relative density Class | Total forest area (million ha) | Percentage of total forest area |
|---|---|---|
| 0.00–0.15 | 25.1 | 13.1 |
| 0.16–0.30 | 35.2 | 18.4 |
| 0.31–0.45 | 48.2 | 25.2 |
| 0.46–0.60 | 44.8 | 23.4 |
| 0.61–0.75 | 24.6 | 12.9 |
| 0.76+ | 13.5 | 7.1 |

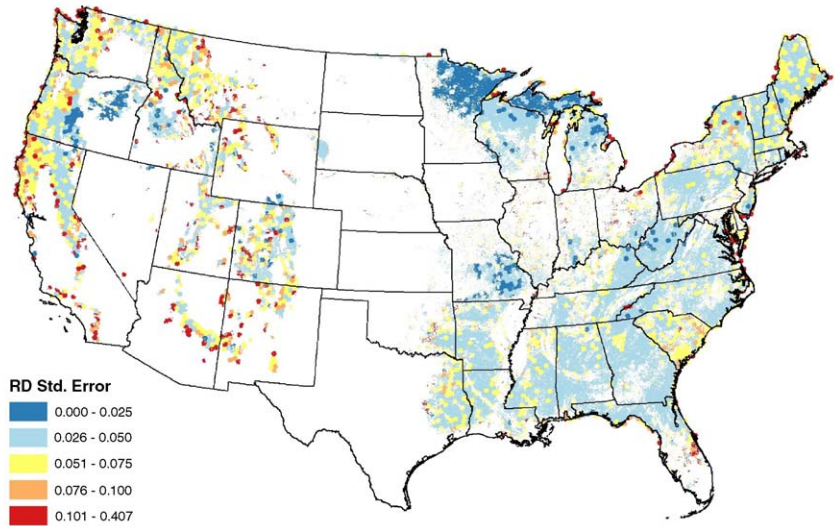


Fig. 3. Standard errors for mean relative density of all RPA inventory observations by EMAP hexagon across the US.

The standard errors (S.E.) associated with mean RDs across the US indicate RD variability within EMAP hexagons (Fig. 3). For the majority of the US, the RD S.E.s are relatively small (between 0.000 and 0.075) indicating uniformity in site occupancies across large scales. Only in forests of the Pacific Northwest and Rocky Mountain states are RD SEs relatively large (>0.076) indicating a diversity of stand RDs across large-scales. Overall, the dispersion of both mean RDs and associated SEs indicate that the majority of forests in the US are fully occupied in a contiguous manner (except for forest/rangeland intermixes of the western US).

A national-scale assessment of the RD of forests of the US has been hindered by the lack of appropriate inventory data and the myriad of tree species that complicate application of most relative density measures. This study presents application of a new RD assessment methodology along with an initial assessment of RD across the US; it is not intended as a site-specific management tool. However, at large scales, this study's methodologies may be used to assess density reduction (fire hazard mitigation) and carbon stock accretion (ecosystem services) opportunities across the US. A national perspective of forest RD may best indicate the results of centuries of forest disturbance across the nation, while this study's results at smaller scales should be interpreted in terms of regional forest dynamics and current stand attributes.

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