Can Live Tree Size-Density Relationships Provide a Mechanism for Predicting Down and Dead Tree Resources?

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***Abstract**: Live tree size-density relationships in forests have long provided a framework for understanding stand dynamics. There has been little examination of the relationship between the size-density attributes of live and standing/down dead trees (e.g., number and mean tree size per unit area, such information could help in large-scale efforts to estimate dead wood resources. The goal of this study was to examine the relationship between standing live, standing dead, and downed dead trees in the context of size-density attributes using a national inventory of forests. Our results indicated that from the lowest to the highest live tree relative stand density, the mean biomass/ha of live trees increased by more than 2,000 percent while the mean biomass/ha of standing dead and downed dead trees increased 295 and 75 percent, respectively. Correlations between downed dead wood and stand/site attributes reached their highest level (r > 0.60) when a stand's relative density exceeded 80 percent. We propose a model for highly stocked stands whereby downed and dead wood biomass may be predicted based on live/dead tree size-density attributes, stand age, and climatic factors. We also provide an alternative model for moderate/low stocked stands whereby potential maximum live biomass may serve as a limit to dead wood resources with stochastic events (e.g., wind/mortality disturbances) as high-impact variables. Overall, the size-density attributes of live/dead trees may help guide the estimation of downed and dead wood attributes in forests.*

Keywords: Downed dead wood, stand density index, size-density, self-thinning, coarse woody debris

Predicting Dead Wood Resources at Large Scales

Forest detritus may be defined as dead organic material in forest ecosystems. For this study, forest detritus will be limited to standing and downed dead woody materials (DDW). Estimates of forest detritus attributes are critical to numerous scientific fields such as carbon accounting (Smith and others 2004, Woodall and others 2008), wildlife habitat assessment (e.g., Bull and others 1997, Harmon and others 1986, Maser and others 1979), and fuel loading estimation (Woodall and

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Monleon 2008). Detritus provides a diversity (stages of decay, size classes, and species) of habitat for fauna ranging from large mammals to invertebrates (Bull and others 1997, Harmon and others 1986, Maser and others 1979). Plants use the microclimate of moisture, shade, and nutrients provided by DDW to establish and regenerate (Harmon and others 1986). Due to the possibility of dwindling detritus habitat for native species and increasing fuel loadings across the United States, comprehensive large-scale inventories of DDW have been established for habitat assessments/wildlife conservation efforts and fire hazard mitigation efforts (e.g., Marshall and others 2000, Rollins and others 2004, Tietje and others 2002, Woodall and Monleon 2008). Worldwide, there has been increased effort in recent years to inventory detrital resources to address greenhouse gas offset accounting and biodiversity concerns (Kukeuv and others 1997, Woldendorp and others 2002, Woodall and others 2008). In 2001, the U.S. began implementing a nationwide inventory of DDW on a subset of inventory plots where standing live/dead trees are measured. An impetus exists to predict DDW for all national inventory plots based on standing live and dead tree attributes (Woodall and others 2008).

To date, efforts to model DDW attributes have been focused at large scales using remotely sensed information and gradient models (e.g., Rollins and others 2004) and at small scales by trying to relate DDW to stand/site attributes (e.g., McCarthy and Bailey 1994, Pyle and Brown 1999, Rubino and McCarthy 2003). Spetich and Guldin (1999) found that DDW accumulation corresponded with increasing site productivity—a function of increased biomass corresponding with increased DDW volume over time. In contrast, Norden and others (2004) found no correlation between DDW volume and basal area in temperate broadleaved forests. Despite the development of models to estimate relationships between forest detritus and stand/site attributes, a sizeable knowledge gap remains in understanding fundamental relationships between forest detritus and basic stand attributes. How does DDW vary by levels of standing live tree density? Can the size/density attributes of both live and dead trees help predict of DDW resources?

Size-Density Relationships in Forest Stands

The size-density of live trees has formed a basis for interpreting/predicting forest stand dynamics for decades (for example see Drew and Flewelling 1979, Gingrich 1967, Krajicek and others 1961, Reineke 1933, Woodall and others 2005). The concept of self-thinning forms the theoretical basis for developing indices of live-tree size-density attributes. Self-thinning is based on the premise that as mean plant size per unit area increases, the number of individuals per unit area decreases (Enquist and others 1998). An inherent component of the self-thinning process is density-induced tree mortality. The forest detritus of standing dead and downed dead wood (DDW) must originate from the mortality/branch shedding of live trees. How closely related are the size-density attributes of live trees in any given forest stand to the attributes of forest detritus?

The goal of this study was to examine the trends in stand-level DDW attributes in relation to the size-density relationships of standing live/dead trees and selected site factors (e.g., climate and stand age) in forests of the United States. The study had three specific objectives: 1) to estimate mean biomass (tonnes/ha) of standing live, standing dead, and DDW by classes of relative density; 2) to test for correlations between standing live, standing dead, DDW biomass, 30-year mean annual maximum temperature, 30-year mean annual minimum temperature, 30-year mean annual precipitation, and stand age by classes of relative density; and 3) to develop conceptual models for estimating DDW by stand/site factors for stands with high and moderate/low relative density.

Data and Methods

The FIA program is responsible for inventorying the forests of the U.S., including both standing trees and DDW on permanent sample plots established across the country (Bechtold and Patterson 2005). Sample plots are established at an intensity of approximately 1 plot per 2,400 ha. If the plot lies in a forested area, field crews visit the site and measure tree and site variables ranging from tree sizes to forest types. FIA standing live/dead tree inventory plots consist of four 7.32-m fixed-radius subplots for a total plot area of approximately 0.07 ha. All standing trees greater than 12.25 cm in diameter at breast height (d.b.h.) are inventoried on the plot, while trees less than 12.25 cm dbh and greater than 2.54 cm d.b.h. are measured on a 2.07-m fixed radius microplot on each subplot. DDW sampling methods on FIA plots are detailed by Woodall and Monleon (2008). DDW with a transect diameter greater than 7.60 cm are sampled on each of three 7.32-m horizontal distance transects radiating from each FIA subplot center at 30, 150, and 270 degrees; DDW pieces of this size are termed coarse woody debris (CWD). Data collected for every CWD piece include transect diameter, length, small-end diameter, large-end diameter, decay class, and species. Fine woody debris (FWD) are DDW pieces with a transect diameter less than 7.60 cm and are sampled on the 150-degree transect on each subplot. Fine woody debris with transect diameters less than 2.54 cm were tallied separately on a 1.83-m slope-distance transect (4.27 m to 6.09 m on the 150-degree transect). Fine woody debris with transect diameters of 2.55 to 7.59 cm were tallied on a 3.05-m slope-distance transect (4.27 m to 7.32 m on the 150-degree transect).

The Forest Inventory and Analysis program of the U.S. Forest Service inventoried standing and down tree attributes across most of the United States between 2003 and 2006 on a total of 4,221 permanent inventory plots. For every inventory plot, the biomass/ha of standing live and dead trees was determined using procedures detailed by Bechtold and Patterson (2005). Plot-level estimates of DDW were calculated using procedures detailed by Woodall and Monleon (2008, section 3.1). To account for data collection errors across the Nation, extreme outliers were removed using 25 times the interquartile range for all classes of FWD (IQR=6.88 tonnes/ha) and CWD (IQR=9.95 tonnes/ha). The relative density of live trees on every plot was determined using the Stand Density Index (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:

$$SDI = tph\ (DBHq/25)^{1.6} \qquad [1]$$

where *SDI* is stand density index, *tph* is number of trees per hectare, and *DBHq* is quadratic mean diameter (cm) at breast height (1.3 m) (Long 1985). SDI has been widely used in even-aged stands because it is independent of species composition. The SDI of even-aged monocultures is typically compared to an empirically observed, species-specific maximum SDI for determining the stand's relative density. Maximum SDI (SDImax) may be defined as the maximum density (tph) that can exist for a given mean tree size (25 cm) in a self-thinning population (Long 1985). To determine relative density (RD), the SDI of any particular stand is compared to the SDImax characteristic of the stand's species composition. Woodall and others (2005) proposed a methodology that estimates the SDImax for any stand based on the mean specific gravity of all trees in a stand to estimate its unique SDImax. By using the summation method (Shaw 2000) to determine the current density of a stand and the Woodall and others (2005) model to predict a SDImax, the RD of all study plots was determined (current SDI/SDImax).

Finally, three climatic variables were selected for correlation with stand-level variables in this study: 30-year mean annual precipitation (PRECIP), 30-year mean annual maximum temperature (TMAX), and 30-year mean annual minimum temperature (TMIN). Data for PRECIP, TMAX, and TMIN were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (4-km grid cell size; PRISM Group 2004). Each of these three variables is represented by a 30-year climate normal. As such, annual precipitation is the mean annual total precipitation from 1971 to 2000. TMAX and TMIN are the mean daily temperature extremes for that period.

Correlations and Means by Classes of Stand Relative Density

The RD of forest stands increased with the mean biomass/ha of standing live trees (Table 1). From an RD of less than 0.10 to more than 0.90, the mean live tree biomass (tonnes/ha) increased by nearly 2,080 percent, while standing dead tree and DDW increased by approximately 295 percent and 75 percent, respectively (Table 1). It appears that the greatest rates of increase in biomass for both standing and DDW were from the moderate to high RD levels (i.e., from a RD of 0.7 to 0.9). In contrast, the biomass of standing live trees had its greatest rate of increase when RD was below 0.5. Using the same RD classes, correlations were conducted between DDW and a selection of stand/site attributes (Table 2). Generally, as a stand's RD increased so did stand/site correlations with DDW. For RDs between 0.00 and 0.10, no correlation coefficient exceeded 0.25. In contrast, the majority of correlation coefficients exceeded 0.40 when RDs

Table 1: Mean biomass (tonnes/ha) and associated standard errors (tonnes/ha) for standing live/dead and downed dead woody materials in forests of the United States by classes of relative density, 2003-2006

Relative Density	Downed, dead woody material	Std. Error	Standing dead	Std. Error	Standing live	Std. Error
0.0-0.1	13.62	0.90	4.29	0.70	10.19	0.40
0.1-0.2	12.81	0.76	3.71	0.34	30.08	0.67
0.2-0.3	14.08	0.74	4.97	0.40	53.22	1.18
0.3-0.4	16.28	0.81	7.15	0.50	78.50	1.48
0.4-0.5	16.82	0.70	8.59	0.57	111.12	2.17
0.5-0.6	16.98	0.88	8.82	0.61	132.02	2.43
0.6-0.7	17.86	1.28	12.74	1.96	163.54	4.69
0.7-0.8	13.63	0.81	7.48	0.71	168.33	5.87
0.8-0.9	21.88	3.42	16.47	2.64	212.85	11.70
0.9-1.0	23.77	2.25	16.94	3.50	222.22	21.27

Table 2: Pearson's correlation coefficients between estimates of downed dead woody material biomass (tonnes/ha) and other stand/site attributes in forests of the United States by classes of relative density, 2003-2006 (Italicized coefficients have p-values> 0.05)

Relative Density	Standing live biomass	Standing dead biomass	30-year mean max. temp	30-year mean min. temp.	30-yr mean annual precipitation	Stand age
0.0-0.1	0.19	0.21	-0.11	*-0.07*	0.14	*-0.03*
0.1-0.2	0.29	0.20	-0.19	-0.12	0.15	*0.02*
0.2-0.3	0.20	0.21	-0.24	-0.18	0.12	*0.02*
0.3-0.4	0.21	0.32	-0.21	-0.14	0.13	*0.01*
0.4-0.5	0.24	0.25	-0.23	-0.21	*0.07*	0.13
0.5-0.6	0.25	0.27	-0.25	-0.21	0.17	0.27
0.6-0.7	0.39	0.36	-0.23	-0.22	0.04	0.21
0.7-0.8	0.25	0.36	-0.23	-0.19	*0.15*	0.24
0.8-0.9	0.68	0.65	-0.26	*-0.20*	*0.17*	0.56
0.9-1.0	0.61	0.56	-0.14	*0.01*	0.42	0.55

exceeded 0.80. For example, stand age only had a correlation coefficient with DDW of -0.03 (p-value> 0.05) when relative density was below 0.10. When a plot's RD was between 0.80 and 0.90, the same correlation had a coefficient of 0.56 (p-value < 0.001). Based on these results, we hypothesize that only stand-level live tree biomass increases consistently with increases in a stand's stocking (i.e., RD). Stand-level biomass for both standing and DDW stand-level only increased at very high levels of stocking, which was further confirmed by DDW correlation results. When constructing models to estimate DDW resources based on stand/site attributes, we propose two models based on a stand's RD: 1) low/moderate and 2) highly stocked.

Conceptual Models of Downed Dead Wood Accretion

A conceptualization of DDW accretion may be developed using a live tree size-density diagram as a framework (Fig. 1). Lightly or moderately stocked stands (in terms of live tree size or biomass) have unpredictable DDW due to management and/or stochastic disturbance events (location D and C in Fig. 1). For stands located in this live tree size-density zone, perhaps the maximum DDW biomass can be predicted based on an estimate of where the maximum size-density self-thinning line is located. The estimate of maximum live tree stand biomass can be reduced by stochastic disturbance and management events to reflect a stand's unique DDW. Although this approach may be "reverse-engineering" of DDW estimates, it provides a conceptual framework that DDW cannot exceed the maximum live tree size/biomass on a site that has been impacted by stochastic disturbance events. When stands are past the zone of imminent mortality and experiencing self-thinning, DDW resources may be fairly predictable using stand and site attributes (e.g., live tree size/biomass and annual precipitation/temperature) (location A and B in Fig. 1). DDW prediction may be relatively straightforward where stands have not been disturbed by stochastic events and management effects.

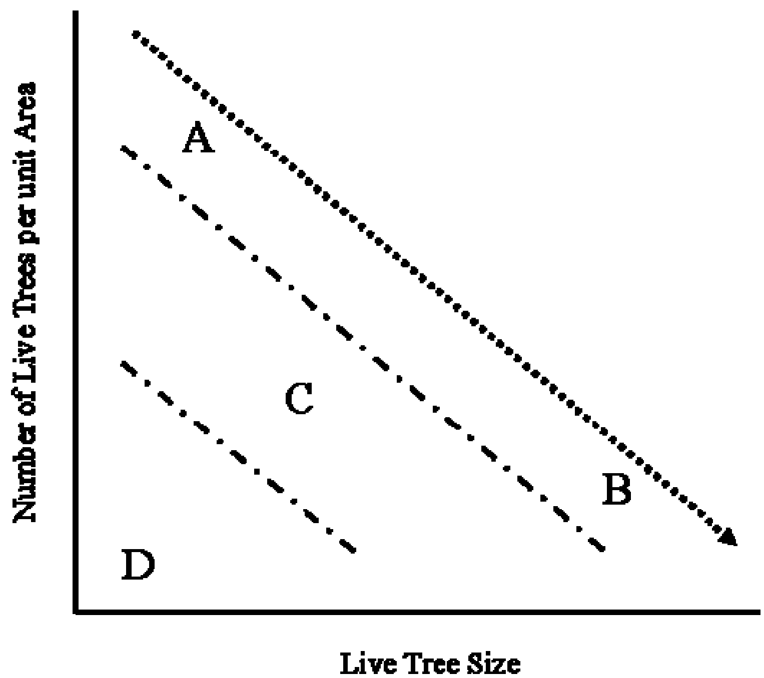

Figure 1: Live tree size density diagram with notable locations in the development of downed dead wood resources: A) high relative density, small live tree size, predictable dead wood resources, B) high relative density, large live tree size, predictable dead wood resources, C) moderate relative density, medium-size live trees, unpredictable dead wood resources, and D) very low relative density, small-size live trees, and highly unpredictable dead wood resources.

Conclusions

Live tree size density attributes of forest stands may provide a framework for understanding and estimating DDW resources in forests across the United States. For stands that are highly stocked in terms of the maximum size-density relationship, DDW resources may be predicted with a reasonable level of confidence due to relatively strong correlations with stand/site attributes. For stands with low/moderate stocking of live trees, an alternative model is proposed whereby the maximum potential DDW biomass is predicted with deductions for highly improbable but high impact disturbance events. We suggest continued research in the area of stochastic event impacts on DDW resources.

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