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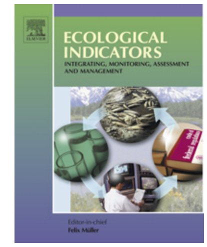

Relationships between forest fine and coarse woody debris carbon stocks across latitudinal gradients in the United States as an indicator of climate change effects

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ABSTRACT

Coarse and fine woody materials (CWD and FWD) are substantial forest ecosystem carbon (C) stocks. There is a lack of understanding how these detritus C stocks may respond to climate change. This study used a nation-wide inventory of CWD and FWD in the United States to examine how these C stocks vary by latitude. Results indicate that the highest CWD and FWD C stocks are found in forests with the highest latitude, while conversely the lowest C stocks are found in the most southerly forests. CWD and FWD respond differently to changes in latitude with CWD C stocks decreasing more rapidly as latitude decreased. If latitude can be broadly assumed to indicate temperature and potential rate of detrital decay, it may be postulated that CWD C stocks may be at the highest risk of becoming a net C source if temperatures increase. The latitude at which CWD and FWD C stocks roughly equal each other (equilibrium point) may serve as an indicator of changes in C stock equilibrium under a global warming scenario. Given the complex relationships between detrital C stocks, biomass production/decay, and climatic variables, further research is suggested to refine this study's indicator.

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1. Introduction

It has been estimated that 35% of the total forest carbon (C) pool in the U.S. is in live vegetation, 52% in the soil, and 14% in dead organic material, such as coarse and fine woody debris USDA, 2004. Coarse woody debris (CWD) is down and dead woody material that is at least 7.62 cm in diameter while fine woody debris (FWD) has a diameter between 0.01 and 7.62 cm (Woodall and Williams, 2005). Terrestrial forest C pools, such as FWD and CWD, often represent a balance between the influx of CO_2 fixed in photosynthesis and the efflux of CO_2 through woody decay processes (Malhi et al., 1999). The decay rate of any individual piece of forest dead wood is determined by substrate quality, microbial activity, air temperature, and available moisture (Yin, 1999). Similarly, the productive capacity of any given forest is partially governed by climatic variables such as temperature (Berry and Bjorkman, 1980). Some studies have suggested that forest detritus production and decay may be in balance (Raich et al., 2006), whereas others have suggested increased detritus decomposition rates due to climate change may ultimately cause forest detritus C pools to become net CO_2 emitters (Hamilton et al., 2002; Sun et al., 2004). Quantifying the dynamics of forest detritus C accumulation and turnover under a scenario of global climate warming is critical to predicting the future inventory of U.S. C stocks. Therefore, developing indicators to predict the effects of possible global warming on CWD and FWD C stocks is highly warranted.

The goal of this study is to examine the relationship between FWD and CWD C stocks and latitude with specific

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objectives including: (1) to estimate mean CWD and FWD C stocks by classes of latitude across the U.S., (2) to conduct 97th percentile regression with CWD and FWD C stocks as dependent on latitude across the U.S., and (3) to suggest a model depicting possible changes in FWD and CWD C stocks as temperatures increase.

2. Methods

2.1. United States' CWD and FWD inventory field methods

The USDA Forest Service's Forest Inventory and Analysis (FIA) program, the only congressionally-mandated national inventory of U.S. forests, conducts a three-phase inventory of forest attributes of the U.S. (Bechtold and Patterson, 2005). The FIA sampling design is based on a tessellation of the land area of the U.S. into hexagons approximately 2428-ha in size with at least one permanent plot established in each hexagon. In phase 1, the population of interest is stratified and plots are assigned to strata to increase the precision of estimates. In phase 2, tree and site attributes are measured for forested plots established in the 2428-ha hexagons. Phase 2 plots consist of four 7.32-m fixed-radius subplots on which standing trees are inventoried.

In phase 3, a 1/16 subset of phase 2 plots are measured for CWD and FWD on transects radiating from each subplot center (Woodall and Williams, 2005). As defined by FIA, CWD are down logs with a diameter $\geq$ 7.62 cm along a length $\geq$ 0.91 m. Information collected for every CWD piece intersected on each of three 7.32-m transects on each FIA subplot are: transect diameter, length, small-end diameter, large-end diameter, decay class, and species. Transect diameter is the diameter of a down woody piece at the point of intersection with a sampling transect. Length is the length of each CWD piece between the small- and large-end diameters. Decay class is a subjective determination of the amount of decay present in an individual log. Decay class one is the least decayed (freshly fallen log), while decay class five is an extremely decayed log typically consisting of a pile of brown, cubicle rot. The species of each fallen log is identified through determination of species-specific bark, branching, bud, and wood composition attributes (excluding decay class five CWD pieces) (for CWD sample protocol details, see Waddell, 2002; Woodall and Williams, 2005; USDA, 2005).

FWD are sampled on the 150° transect on each subplot. FWD with diameters less 2.54 cm were tallied separately on a 1.83 m slope distance transect (4.27–7.32 m from subplot center on the 150° transect). FWD with transect diameters of 2.55–7.59 cm were tallied on a 3.05 m slope–distance transect (4.27–7.32 m on the 150° transect) (for more information on class definitions see Deeming et al., 1977). FWD sampling methods on FIA plots are detailed by Woodall and Williams (2005) and USDA (2005).

Although FIA data provides the only systematically sampled inventory of FWD and CWD across most of the United States, the measurement of forest detritus is still prone to errors and subjectivity (Westfall and Woodall, 2007). However, its has been found that FWD and CWD measurement errors in the FIA program are largely unbiased (Westfall and Woodall, 2007), thus a national assessment of thousands of plots should serve as an appropriate dataset for exploration of study objectives.

2.2. Data and analysis

Inventory plots ($n = 5528$ plots) were sampled in forested conditions across the United States for CWD and FWD between 2001 and 2005 by the FIA program in 45 of the conterminous 48 states (sampling not established in Mississippi, Wyoming, and New Mexico).

CWD and FWD C stocks were estimated using line-intersect weight per unit-area estimators and C content conversion factors (Woodall and Williams, 2005). Line-intersect sampling estimators were used to determine weight per unit-area estimates for sample plots based on subplot sampling transects. C stocks were then determined by multiplying biomass estimates by a C content conversion factor (Birdsey, 1992; Waddell, 2002). C storage in CWD (C_{CWD}) was calculated using Eq. (1):

$$C_{CWD} = \sum_{i=1}^{n}(cG)\left[\left(\frac{\pi}{2L}\right)\left(\frac{V_m}{l_i}\right)f\right] \tag{1}$$

where n is the number of pieces, c is the proportion of C in the mass of the piece, f is the conversion factor for unit-area values (10,000), G is the estimated specific gravity of the piece reduced by a modeled decay reduction factor (oven dry), L is the total length of the transect corrected for slope (m), V_m is the volume of an individual piece (m^3), and l_i is the length of the individual piece (m) (Woodall and Williams, 2005). Birdsey (1992) provides mean conversion factors (c) for both softwood (0.521) and hardwood species (0.491). Waddell (2002) provides decay reduction factors for various CWD decay stages for reducing the specific gravity of CWD pieces based on the state of decay. C storage in FWD (C_{FWD}) was calculated using Equation (2):

$$C_{FWD} = \sum_{i=1}^{n}\frac{(Gacsk)}{L}n_i\bar{d}_i^2 \tag{2}$$

where G is the specific gravity of the piece, a is the nonhorizontal lean angle correction factor for FWD pieces, c is the proportion of C in the FWD, s is the slope correction factor because FWD is measured along a slope-distance transect, k is a constant representing both unit conversion and a constant for FWD piece lengths (1.234), L is the slope length of the transect (m), n_i is the number of pieces of FWD in size class i, and d_i is the mean diameter (cm) of pieces within size class i. Because species data are not collected for FWD, we applied the mean value of the C proportions for softwoods and hardwoods (0.506) to c. Additionally, G was based on the mean specific gravity of all CWD pieces on the same sample plot. C storage for the smallest FWD size class (<0.64 cm) was not included in plot totals because this stock is included in forest floor measurements of litter.

The mean and standard error for CWD and FWD C stocks were estimated by classes of latitude (4°). Significant differences between means were tested using an ANOVA model (differences significant at $p = 0.05$). In order to estimate the