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Estimating litter carbon stocks on forest land in the United States

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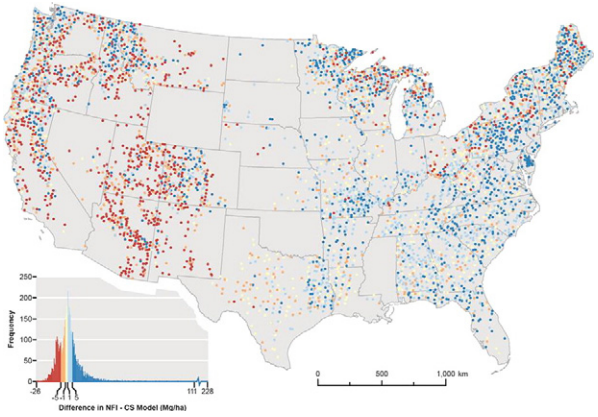
HIGHLIGHTS

- Litter carbon in forests is a relatively small but important part of carbon budgets.
- The US has been overestimating the contribution of litter carbon in forests.
- IPCC default values for temperate forests may lead to overestimates in litter carbon.
- In situ measurements of litter in forests of the US have improved model predictions.

GRAPHICAL ABSTRACT



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ABSTRACT

Forest ecosystems are the largest terrestrial carbon sink on earth, with more than half of their net primary production moving to the soil via the decomposition of litter biomass. Therefore, changes in the litter carbon (C) pool have important implications for global carbon budgets and carbon emissions reduction targets and negotiations. Litter accounts for an estimated 5% of all forest ecosystem carbon stocks worldwide. Given the cost and time required to measure litter attributes, many of the signatory nations to the United Nations Framework Convention on Climate Change report estimates of litter carbon stocks and stock changes using default values from the Intergovernmental Panel on Climate Change or country-specific models. In the United States, the country-specific model used to predict litter C stocks is sensitive to attributes on each plot in the national forest inventory, but these predictions are not associated with the litter samples collected over the last decade in the national forest inventory. Here we present, for the first time, estimates of litter carbon obtained using more than 5000 field measurements from the national forest inventory of the United States. The field-based estimates mark a 44% reduction (2081 ± 77 Tg) in litter carbon stocks nationally when compared to country-specific model predictions reported in previous United Framework Convention on Climate Change submissions. Our work suggests that Intergovernmental Panel on Climate Change defaults and country-specific models used to estimate litter carbon in temperate forest ecosystems may grossly overestimate the contribution of this pool in national carbon budgets.

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1. Introduction

The Intergovernmental Panel on Climate Change recognizes litter carbon (C) as one of five C pools in forest ecosystems included in the Agriculture, Forestry and Other Land Use sector of annual national greenhouse gas inventories (IPCC, 2006). In the United States (US), the national forest inventory (NFI) conducted by the US Department of Agriculture, Forest Service, Forest Inventory and Analysis program is used to compile annual estimates of forest C stocks and stock changes for the national greenhouse gas inventory (US EPA, 2015). For more than a decade, tree- and site-level variables related to each forest ecosystem C pool have been measured in the NFI (O'Neill et al., 2005a; Woodall and Monleon, 2008, and Domke et al., 2013). In recent years, estimation approaches have been developed that rely directly on measurements from the forest ecosystem attributes of interest (US EPA, 2015), reducing the uncertainty associated with the estimates of C stocks and stock changes in the national greenhouse gas inventory and improving their sensitivity to natural and anthropogenic disturbances.

The US uses a stock-difference C accounting approach (IPCC, 2006) in United Nations Framework Convention on Climate Change reporting, requiring estimates of litter C stocks, defined in this study as the pool of organic C above the mineral soil (i.e., litter (Oi), fulvic (Oe), and humic layers (Oa)) including woody fragments with large-end diameters of up to 7.5 cm (Woodall et al., 2012), on every NFI plot across space and time. Before extensive field data were collected on non-live tree attributes, the Forest Service estimated litter C with a country-specific model developed with data obtained from the literature using geographic region (a proxy for climate), forest stand age (an indication of time since disturbance), and species composition (an indication of the source and character of organic matter) as predictor variables (Smith and Heath, 2002). Significantly, this model has served as a primary source of information used in Intergovernmental Panel on Climate Change guidance for temperate forest ecosystems in nations lacking litter C estimates in their NFIs (IPCC, 2006 and US EPA, 2014).

Globally, the litter C pool accounts for an estimated 5% (43 Pg) of all forest ecosystem C stocks (Pan et al., 2011). In contrast, the country-specific model (Smith and Heath, 2002) used in the 1990–2012 US national greenhouse gas inventory predicted litter C at 11.7% (5056 Tg) of total forest C stocks (43,126 Tg), with an estimated net annual increase of 14 Tg C yr^{-1} over the last 5 years (US EPA, 2014). Although the US' country-specific model uses NFI plot attributes to estimate litter C stocks, these predictions are not associated with the litter samples collected over the last decade by the Forest Inventory and Analysis program (O'Neill et al., 2005b and Woodall et al., 2012). General comparisons of the country-specific model predictions to the NFI estimates suggest that the country-specific model does not accurately characterize the litter C in forests of the US.

Developing data-driven models to characterize the litter C pool is challenging as it can be highly variable (Böttcher and Springob, 2001; Schulp et al., 2008 and Woodall et al., 2012) with large differences between forest types on the same soils (Ladegaard-Pedersen et al., 2005) and variations in thickness across short distances (Smit, 1999). This pool's vulnerability to disturbance, particularly wildfire (Stinson et al., 2011), also contributes to the variability (Pan et al., 2011). There are few NFIs with observations of litter C with which to build models and evaluate litter C predictions at regional or national scales (Kurz and Apps, 2006 and Keith et al., 2009).

The Forest Service has been measuring litter attributes, including C content and bulk density, on a subset of the NFI plots since 2001 (O'Neill et al., 2005b and Woodall et al., 2012). Here, we show how these data support a new approach to litter C estimation. Specifically, we: 1) demonstrate the inadequacies of the country-specific model currently used relative to estimates of litter C stocks obtained from the NFI; 2) develop a new modeling framework based on litter measurements in the NFI and stand, site, and climatic variables; and 3) use the new modeling framework to estimate litter C in the 2015 US national greenhouse gas inventory.

2. Methods

In this study, we used observations of litter variables – total C (organic and inorganic) concentration in percent of the litter sample, oven-dry sample weight of the litter material, and the per-unit-area estimate of medium and large fine woody debris – to estimate C from the annual NFI (2001 — 2012). The sample included 4553 inventory plots and 5263 unique forest conditions (i.e., domains mapped on each plot using land use, forest type, stand size, ownership, tree density, stand origin, and/or disturbance history — there may be multiple conditions on a single inventory plot), hereafter referred to as plots (Bechtold and Patterson, 2005) in the conterminous US (Fig. 1a). The annual NFI includes a nationally consistent sampling frame and plot design so the methodologies established for replacing the country-specific model predictions of litter C stocks could be applied nationally to enable stock-difference C accounting. Note that litter samples from Mississippi, Oklahoma, and Wyoming were not available at the time of this study (Fig. 1a).

2.1. Plot design and sampling

The Forest Inventory and Analysis program employs a multi-phase inventory, with each phase contributing to the subsequent phase. First, current aerial photography (e.g., National Agriculture Imagery Program, USDA Farm Services Agency, 2008) is used in a prefield process to examine all sampling points (i.e., plot locations) to determine whether a forested condition exists at each point. Next, each sample point is assigned to a stratum using satellite imagery or thematic products (e.g., National Land Cover Database, Jin et al., 2013) obtained from satellites. A stratum is a defined geographic area (e.g., state or estimation unit) that includes plots with similar attributes; in many regions strata are defined by predicted percent canopy cover. Base intensity permanent ground plots are distributed approximately every 2428 ha across the 48 conterminous states of the US in four geographic regions (Fig. 1). Each permanent ground plot comprises a series of smaller fixed-radius (7.32 m) plots (i.e., subplots) spaced 36.6 m apart in a triangular arrangement with one subplot in the center (Fig. 2). Tree- and site-level attributes – such as diameter at breast height (dbh) and tree height – are measured at regular temporal intervals on plots that have at least one forested condition (i.e., there may be multiple condition plots) defined in the prefield process (USDA Forest Service, 2014a). Litter samples are collected along with other non-standing tree ecosystem attributes (e.g., downed dead wood) on every 16th base intensity plot distributed approximately every 38,848 ha (Bechtold and Patterson, 2005). Although sample intensity was 1/16th of the base plot intensity during this study's time period (2001–2012), there may be opportunities to increase the sample intensity in future NFIs.

Litter variables are sampled as a complete unit on plots adjacent to subplots 2, 3, and 4 using a circular sampling frame that is 30.48 cm in diameter (Fig. 2; USDA Forest Service, 2011). At each sample point, the entire litter thickness (i.e., duff and litter layers) is measured to the nearest 0.25 cm at points in each cardinal direction within the sampling frame to the point where mineral soil (A horizon) begins (O'Neill et al., 2005b). The entire litter layer (excluding live vegetation, woody debris > 0.64 cm in diameter, rocks, cones, and bark) within the confines of the sampling frame is removed for lab analysis. Litter samples are analyzed for bulk density, water content, total C, and total N (O'Neill et al., 2005b) and the laboratory results are managed as part of the Soils Lab Table (SOILS_LAB) in the publicly available Forest Inventory and Analysis database (USDA Forest Service, 2014b and Woodall et al., 2010).