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Vertical distribution and persistence of soil organic carbon in fire-adapted longleaf pine forests

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ABSTRACT

Longleaf pine (*Pinus palustris* Miller) forests in the southern United States are being restored and actively managed for a variety of goals including: forest products, biodiversity, C sequestration and forest resilience in the face of repeated disturbances from hurricanes and climate change. Managed southern pine forests can be sinks for atmospheric CO_2 in forest biomass; however, the persistence of biomass in the environment or in forest products is limited, thus making soil C the primary long-term pool. Little is known about the size of extant soil C pools, residence time of soil C or the role that frequent burning plays in C stabilization in longleaf pine ecosystems. We sampled soil from a chronosequence of longleaf pine stands ranging in age from 5 to 87 years to quantify the vertical distribution of soil organic carbon (SOC) stocks; both oxidizable (SOC_{OX}) and oxidation resistant (SOC_R) fractions, pyrogenic carbon (PyC) and the mean residence time (MRT) of SOC and its associated fractions. SOC stocks (0–1 m) ranged from 44.1 to 98.1 ($\bar{x}$ = 77.0) Mg C ha^{-1}, and no effect of stand age or biomass accumulation on SOC stocks was detected. Soil C accumulation was associated with elevated clay and extractable Fe contents. While SOC concentration declined with soil depth, the proportion of SOC_R in SOC increased with depth. PyC was a minor component of soil C, representing 5–7% of SOC and the proportion was not depth dependent. The MRT of SOC was hundreds of years near the surface and many thousands of years at depth. Though SOC_R was less abundant than SOC_{OX}, SOC_R MRT was an order of magnitude greater than SOC_{OX} MRT and had a strong influence on bulk SOC MRT. The majority of the PyC was in the less persistent SOC_{ox} and not associated with long-term C storage in soil. Despite the flow of C from biomass in the form of decay products, litter fall, root turnover and pulses of PyC, these soils preserve little of recent inputs, which may be rapidly oxidized, lost to the atmosphere from periodic fires or, in the case of PyC, may be transported out of the system via erosion. Our results indicate that these soils were not strong sinks for atmospheric CO_2, especially when compared to C accumulation in biomass.

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1. Introduction

A key component of sustainable forestry is the responsible management of soil carbon (C) to ensure that site quality is maintained (Johnsen et al., 2001). Aggrading forests can rapidly accumulate atmospheric CO_2 in biomass during the early stages of a rotation,

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but the persistence of this biomass C is ephemeral, thus soil is the primary long-term C pool. Stabilization of organic matter in soil is dependent on chemical composition, climate, moisture retention, soil minerology, and pyrogenic transformation, as well as physical isolation from environmental fluctuations at depth (Oades, 1988; Batjes, 1996). These factors lead to considerable variability in soil C quantity and residence time among and within sites and regions. In the southern United States, rapid turnover of soil C inputs from forests may be facilitated by coarse sands and low-activity clay mineralogy that limit long-term retention (Richter et al., 1999).

Longleaf pine forests in the southern United States are being restored and actively managed to provide forest products and a variety of ecosystem services such as biodiversity and disturbance-resistant long term C storage (Churchill et al., 2013). Longleaf pine occurs on a variety of soil types from coastal sands to eroded upland clay soils, but little is known about the quantity and persistence of soil C as well as the role of soil properties on the rate of soil C accumulation across its range. Longleaf pine ecosystems were a dominant forest type in the southeastern United States sustained by frequent low intensity fires (Frost, 1993; Schmidtling and Hipkins, 1998). As an example, in the Kisatchie National Forest in Southwest Louisiana, mean fire return from 1650 to 1905 was determined to be 2.2 years (Stambaugh et al., 2011). In the 19th and early 20th centuries the majority (>95%) of the longleaf forest was logged and converted to agriculture (Frost, 2006), and subsequent management led to considerable loss of topsoil. Thus, most current longleaf pine sites experienced millennia of frequent, low intensity fire followed by removal of forest cover, interruption of fire cycles and soil degradation. The long history of frequent fire prior to European settlement and current use of fire in restored systems has resulted in pulses of pyrogenic C (PyC) also referred to as "black carbon" into the soil. PyC residence time is estimated to be on the centennial time scale (Singh et al., 2012; Knicker et al., 2013), thus it can be an important avenue of soil C sequestration in terrestrial systems (Jaffe et al., 2013; Bird et al., 2015).

PyC found in soil is the result of incomplete combustion of biomass under low oxygen conditions. PyC is composed of a variety of C compounds; being a class rather than a specific material (Schmidt and Noack, 2000; Masiello, 2004; Preston and Schmidt, 2006; Hammes et al., 2008). In brief, fire transforms these organic compounds into a spectrum of amorphous materials dominated by fused aromatic rings. This material ranges from partially burned woody material to char. PyC becomes more recalcitrant along the spectrum associated with aromatic condensation, persisting from hundreds to thousands of years (Hammes et al., 2008; Ascough et al., 2009). There is a misconception that PyC formed from biomass under native environmental conditions is broadly inert and with long residence times in soil. Knicker et al. (2013) found that pyrogenic organic matter (PyOM) formed naturally in a severe forest fire and incorporated into the mineral soil had residence times 5–6 times longer than SOM in soils unaffected by fire. This increases the C sequestration potential of forest soils, but residence times were still modest, ranging from 500 to 600 years. The PyC products have a range of biochemical stability, though in general PyC formed at low temperature has higher O:C ratios and is more readily degraded than PyC formed at high temperatures (Inoue and Inoue, 2009; Spokas, 2010; Ascough et al., 2011). The amount of biomass converted to PyC is dependent on feedstock chemistry, combustion temperature and oxygenation. Preston and Schmidt (2006) estimated a conversion rate, of combusted organic matter, of 1–6% in boreal systems, while others contend that the mean conversion rate is substantially higher e.g. 5–15% (Santin et al., 2016).

To better understand the composition of extant soil C pools and assess the soil C sequestration potential, quantitative data are needed on the vertical distribution of C within the soil profile and persistence of C in soil. Key questions include: (1) How are SOC stocks partioned between active and resistant fractions and how much is PyC contributing to them? (2) How long does SOC persist and does PyC contribute long-term persistence? (3) Which edaphic factors are associated with SOC stocks and persistence? To address these questions we analyzed the vertical distribution and persistence of SOC to a depth of 1 m in fire-adapted longleaf pine forests aged 5–87 years old at sites with contrasting soil edaphic properties. A total of 14 stands were studied across the range of the species in the southern United States. Bulk SOC was chemically fractionated into resistant and oxidizable pools, then radiocarbon abundance measurements were applied to calculate quantitative estimates of the relative persistence of those fractions. Benzene Polycarboxylic Acid (BPCA) markers were used to quantify and characterize PyC (Glaser et al., 1998; Brodowski et al., 2005). This allowed us to analyze the effect of forest stand development (age, stand characteristics, above and belowground biomass C) and soil properties (depth, bulk density, texture, extractable iron) on the vertical distribution and persistence of C in soil. Our overall goal was to assess SOC pools by resistance to oxidation, PyC content, and mean residence in longleaf pine stands to better understand the legacy of past land use, frequent forest fires and current forest management on soil C stocks. Such quantification of soil C stocks will contribute to regional and national efforts to model C storage in soil and guide long-term management efforts.

2. Methods

2.1. Study areas

Sites selected for this study were part of a larger effort to quantify forest C density in longleaf pine forests and were previously described in detail (Samuelson et al., 2014, 2017). A chronosequence of 14 managed longleaf pine stands were selected for intensive sampling and characterization. They were located across the east-west range of the species from the Atlantic Coast Flatwoods (ACF), to the Southern Piedmont (SP) extending to the Western Coastal Plain (WCP) Major Land Resource Areas (MLRAs) in the southern United States (NRCS, 2006). Stands varied in age and basal area within each MLRA and soil characteristics varied between MLRAs (Table 1). Study sites were selected primarily on forest stand characteristics typical for each MLRA and active management with cyclical prescribed burning. Five SP stands located on Fort Benning Military Installation, Columbus, Georgia were sampled in 2012. Five WCP stands located on the Vernon District of the Kisatchie National Forest in Vernon Parish, Louisiana were sampled in 2013. Four ACP stands located on Camp Lejeune Military Installation, Jacksonville, North Carolina were sampled in 2014. Stands in ACP were typified by deep sands while those in SP and WCP had greater clay and silt fractions.

Detailed characterization of forest carbon stocks including overstory, understory, ground cover, taproots, coarse roots, fine roots, dead snags, woody debris, litter and duff were presented by Samuelson et al. (2014, 2017). All stands were even-aged with a minor component of volunteer *Pinus taeda* or hardwood recruitment and actively managed with an approximate three year fire return cycle. Four of the older stands were naturally regenerated and the others were planted.

2.2. Soil collection

The approach for defining study plots and collecting soil samples was adapted from the Global Terrestrial Observing System (GTOS) protocol for soil and root sampling (Law et al., 2008).