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The effect of organic matter manipulations on site productivity, soil nutrients, and soil carbon on a southern loblolly pine plantation

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ABSTRACT

Forest harvesting intrinsically removes organic matter and associated nutrients; these exports may impact soil productivity and soil carbon stores of managed forests. This study examined the effect of manipulating forest floor and harvest residue inputs on nutrient availability and carbon content in the context of intensive forest management. Treatments were applied 15 years prior to this study and included removal and addition of forest floor and harvest residues, and a reference. We examined stand volume, litterfall, root biomass and foliar N and P at year 14 or 15. Soil moisture and temperature (0–10 cm) and available N and P in the O and 0–20 cm depths were measured once per month during year 15. Soil carbon and nitrogen were measured on whole soils as well as two density fractions in the O-horizon, 0–20, 20–40, and 40–60 cm soil depths at year 15. In general, many of the initial responses found by an earlier study (age 10) have dissipated. Standing volume in the added treatment was 31% higher than the removed, but no significant difference was found between the removed and reference treatments. The added treatment resulted in higher concentrations of N in the light and heavy density fractions of the 0–20 cm depth, which led to higher mass of N in both of these fractions. The added treatment had the greatest whole soil heavy fraction N mass. There were no differences in available N in the O-horizon or 0–20 cm depth as tested using ion exchange membranes; however available P was significantly lower in the O-horizon of the removed treatment (37% lower than the reference). Bole volume was correlated with some measures of total and available N and P in the O and 0–20 cm soil horizons, suggesting that increases in growth found in the added treatment were a result of additional nutrients. There were no significant differences between C concentration or mass of the 0–20 cm or 20–40 cm soil depths between the treatments; however the added treatment had significantly more (51% more than the reference) carbon at the 40–60 cm soil depth. The added treatment had a significantly higher C:N relative to the reference in the 20–40 cm (21.0 and 14.5, respectively) and 40–60 cm (18.0 and 11.4, respectively) depths, suggesting that relatively fresh, undegraded organic matter had enriched this depth. This additional carbon sequestered at depth could contribute to a long-term soil carbon pool. The results of this study suggest that higher intensity use, such as forest floor removal and whole tree harvest, of these forests may not impact long term productivity at this site with typical soil nutrient status; however, more research is necessary to determine the mechanism(s) of this resilience.

1. Introduction

In the United States, standard harvesting operations of intensively managed plantations utilize bole-only harvesting techniques with best management practices (BMPs) that redistribute the tops, branches and needles across the site. However, if these BMPs are not followed then higher levels of nutrient and carbon removals could impact long-term soil productivity and soil carbon stores, especially on sites with coarse-textured soils and low soil organic matter (Powers et al., 2005). Furthermore, there are national level movements underway that may influence managers to intensively utilize residues from forest harvesting operations. For example, the Energy Independence and Security Act (EISA) of 2007 has set a goal of 36 billion gallons/year of biofuels by 2022 and, in general, set goals and regulations to reduce the United States' dependence on

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foreign sources of oil (EISA, 2007). There are also developing markets for biomass for electricity generation. While no single source of biomass will provide the feedstock for this effort (Kenney et al., 2013), harvest residues represent an abundant, and currently low demand, biomass feedstock that could be used to generate renewable electricity and biofuels. Forest harvesting, bole-only or for biomass, intrinsically removes organic matter and associated nutrients; these exports may impact long-term soil productivity and soil carbon stores of managed forests.

Litter and slash are sources of soil organic matter (SOM) which is potentially a long-term sink for atmospheric carbon dioxide (CO_2). Soil organic matter plays a significant role in soil function; in particular, cation exchange capacity, soil structure, aeration, water holding capacity, and soil strength. Decomposing SOM provides the majority of the mineralized forms of nitrogen (N). Collectively, these characteristics of SOM play an integral role in sustaining site productivity (Fisher and Binkley, 2000).

Forest productivity is typically defined as the growth and maintenance of a forest (e.g. gross or net primary production). When dealing with forests grown for wood production, many forest managers are primarily interested in bole volume. Bole volume along with litterfall and root mass is how we have measured forest productivity in this paper. Detecting a decline in forest productivity is challenging due to the effects of tree genotype, management practices, plasticity of trees to adapt to a site, and changes in state factors (e.g. climate) at potentially masking any trends in productivity (Richardson et al., 1999; Morris and Miller, 1994). Furthermore, productivity declines may only occur after some threshold has been exceeded (Richardson et al., 1999). One suggestion for detecting changes in the ability of a site or soil to grow trees is to use soil indicators (Burger and Kelting, 1999; Richardson et al., 1999).

Most forest floor removal studies that include a whole tree harvesting treatment have shown no significant effect on stand productivity (Powers et al., 2005; Ponder, 2008; Zerpa et al., 2010; Ponder et al., 2012). The North American long-term soil productivity (LTSP) network found no significant differences in tree productivity at age 10 after whole tree harvesting and floor removal on 18 sites across North America (Powers et al., 2005). However, at the regional level some conflicting treatment effects have been observed. For example, an intensively managed loblolly pine (*Pinus taeda* L.) plantation on the Lower Coastal Plain of North Carolina showed no significant differences in the aboveground biomass at either 5 or 10 years after treatment establishment (Li et al., 2003). On the other hand, Gulf Coastal Plain sites with noted phosphorus deficiencies exhibited bole volumes 15–66% less than the bole only removal treatment 5 years following complete removal of O-horizon and harvest residues (Scott et al., 2004). It appeared that site quality played an important role in stand response since the largest reductions in growth occurred on sites with the lowest site quality.

Changes in site productivity occurring after whole tree harvest are not always detected early in stand development (Sanchez et al., 2006); decline in productivity may not appear until subsequent rotations. Furthermore, changes in productivity may decline into perpetuity or reach a new steady state that is consistent with the management regime (Worrell and Hampson, 1997). In Scandinavia, several long-term studies examined the effects associated with whole tree harvesting for biomass have shown immediate impacts to stand productivity and after subsequent whole-tree thinning of stands regenerated after whole tree clear-cut harvesting (Helmisaari et al., 2011). The impact of intensive organic matter removal on long-term site productivity is more likely to be observed on nutrient poor sites, which often contain coarser textured soils. Furthermore Ponder (2008), suggested that the effect of O-horizon and harvest residue removal may not be apparent until crown closure when nutrient demands of the soil are highest, a hypothesis consistent with results from the Scandanavian study by Helmisaari et al. (2011). To determine the effects of intensive organic matter removal on stand productivity whole tree harvested stands from a range of sites need to be followed through an entire rotation, and preferably for multiple rotations (O'Hehir and Nambiar, 2010).

Relative to standard harvesting operations, intensive organic matter removal may alter soil carbon cycling by removing a source of soil carbon, causing a larger disturbance to the soil surface, and changing temperature and moisture regimes which influence heterotrophic respiration rates. Changes caused by these operations may lead to a loss of soil carbon capital, with the magnitude of change dependent on forest and soil type (Johnson and Curtis, 2001; Jandl et al. 2007; Nave et al. 2010). Nave et al. (2010) reported an 8% average reduction in soil carbon stocks after bole-only clear-cut harvesting over all forest and soil types studied. These losses were primarily caused by reduced litter layer mass as a result of lower organic matter inputs from growing trees; in contrast, harvesting had little significant effect on mineral soil carbon or lead to increases as a result of incorporation of harvesting residues into the mineral soil. Due to the importance of slash incorporation in the studies examined by Nave et al. (2010) this would suggest that whole tree harvesting may be at higher risk of detrimentally impacting soil carbon stores. However, whole tree harvesting in addition to O-horizon removal has been shown to have little impact on soil carbon stores after 5 and 10 years in soils with moderate levels of soil carbon (Powers et al., 2005; Sanchez et al., 2006).

In many harvesting operations soil and slash are displaced, so that some areas may have exposed mineral soil (slash and O-horizon removed), while other areas may have additional O-horizon and slash. Adding organic matter to the forest floor following a harvest can increase soil nutrient capital and improve growth of aboveground biomass (Sanchez and Eaton, 2001; Zerpa et al., 2010). However, this process is costly and may not always achieve positive results (Sanchez and Eaton, 2001). Zerpa et al. (2010) observed an increase in available N, tree growth, and litterfall 10 years after harvest with the addition of organic matter (i.e., doubling the forest floor compared to reference). The difference in total N resulted in a significantly lower C:N ratio of the O-horizon in the doubled OM treatment. This was attributed to improved N quality in the Oi and Oe layers from the addition of organic matter. Consequently, adding organic matter following harvest increased soil nutrient capital, nutrient availability, and therefore tree productivity.

In this study, we utilize an organic matter addition treatment in addition to a removal treatment to explore the role that site quality has in affecting loblolly pine productivity 15 years after planting. This study is a follow-up on Zerpa et al. (2010) who examined these sites after 10 years of tree growth. We hypothesize that stand productivity is driven by soil resource availability, especially N and P, and if these pools decline then overall stand productivity may decline. Therefore, adding or removing nutrients from sites with nutrient limitations on growth should result in equal but opposite responses to soils and site productivity. Thus, the objective of this research was to assess changes in site productivity by examining the effect of manipulating forest floor and harvest residue inputs; specifically, we evaluated how these manipulations affect nutrient availability and soil C content in the context of intensive forest management 14 years after study installation.

2. Materials and methods

2.1. Site description

The Millport Organic Matter Study (Zerpa et al., 2010) is located in Lamar County, Alabama, USA (33°32′22.87″N, 88°77.53″W). The