WOODY BIOMASS RESIDUE RETENTION EFFECTS ON SOIL QUALITY INDICATORS IN THE LOWER COASTAL PLAIN OF GEORGIA AND NORTH CAROLINA

by

ANCHAL BANGAR

(Under the Direction of Lawrence Morris and Daniel Markewitz)

ABSTRACT

Levels of woody biomass retention (no retention guidelines- all operationally accessible residue removal, 15 or 30% retention, or no residue harvest) and the post-harvest redistribution of these materials (distributed or clustered) were evaluated for impacts on soil quality indicators in Georgia and North Carolina. Overall, the treatment effects on soil C and N were minimal. However, soil compaction increased following harvesting and site-preparation. Windrow or pile size after site preparation did not significantly affect the soil organic carbon, soil organic nitrogen or soil extractable macro-nutrients (Ca, Mg, PO_4-P, K). In the case of ion-exchange resin recoverable macronutrients, no elements were affected by pile size but K did decrease with distance from windrows. In general, in the first year after harvest, woody residue retention levels had few impacts on measured soil attributes.

INDEX WORDS: Biomass harvest, Soil quality, Residue retention, Windrow, Exchangeable macro-nutrients

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DEDICATION

I am dedicating this thesis to my loving husband without whom this thesis would not have been written, who stayed with me through thick and thin, and is my source of encouragement. Nothing was possible without you!

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CHAPTER I

Introduction and Literature Review

Introduction

Intensively managed loblolly pine (*Pinus taeda L.*) plantations are an important source of energy production. Use of wood as a renewable energy source can be beneficial because of low production cost, as well as reduced fossil fuel greenhouse gas emissions. New federal policies like the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 have been formed to encourage use of renewable transportation fuels (i.e., biofuels), or to require renewable power (i.e. bioenergy) generation (Database of State Incentives for Renewable Energy, 2013). The Renewable Fuel Standard (RFS) program was created to achieve a goal of 36 billion US gallons of biofuel production annually at a national level by the year 2022. The Renewable Portfolio Standards (RPS) have been implemented independently in some states that require the production of 25% of the electrical energy from renewable energy sources. The renewable energy can be obtained from sources like biomass, solar, wind, geothermal, and/or hydropower. Currently, there are 29 states with a mandated RPS and seven states with an RPS goal detailing the percentage of electricity that must be generated from renewable energy sources that the state will meet by a certain time in the future. Seven of the 15 states in the southern US have an RPS target ranging from 15 percent (North Carolina, Oklahoma, and Virginia) to 25 percent (Delaware and West Virginia).

Due to these new policies, there is an expected increase in demand for energy produced using woody biomass from forests. The increase in demand may lead to an increase in harvesting levels of both round wood and forest residue. Logging slash or non-merchantable logging residues like small diameter trees, tops, and limbs that are typically left on the harvest site in conventional harvesting may see increased levels of harvest removal (Titus et al., 2010). The Energy Information Administration (EIA 2010) reports that woody biomass contributes 41% of total renewable energy in the USA and is the source of 53% of bio-energy production. The residues that are otherwise non-merchantable can be used as a beneficial source for bio-energy production.

Most states follow Forestry Best Management Practices (BMPs) that are designed to minimize sediments in streams and to protect against erosion, but they do not specify protocols for the removal of slash or other woody biomass residues. Although forest certification systems such as the Forest Stewardship Council and Sustainable Forestry Initiative systems were revised in have been recently revised to emphasize environmental impacts of management, biomass harvesting was not addressed. Due to rising concerns over bio-energy harvests, interest has risen nationwide to update existing biomass harvesting guidelines (BHGs). Seven states including Wisconsin, Michigan, Kentucky, Missouri, Minnesota, Maine and Pennsylvania have already developed new biomass harvesting guidelines. Michigan, for example, has developed BHGs that recommend leaving 1/6 to 1/3 of biomass at the site following harvest (Michigan Department of Natural Resources and Environment, 2010). There is a need to develop guidelines that focus on biomass harvesting of residue to address increasing energy demands as well as keeping the soil sustainable for future production.

The objective of this study is to quantify the effect of different levels of biomass harvesting on forest floor and mineral soil nutrient content (i.e. C and N) as well as to assess the effect of harvesting loblolly pine plantations and site preparation operations on soil bulk density in the lower coastal plains of Georgia and North Carolina. An additional objective was to evaluate how concentrating residues on the site as a result of method of retention or mechanized site preparation affects adjacent soil properties. Specifically, we evaluated the relationship between distance from residue piles and soil moisture, soil temperature, CO_2 efflux and nutrient availability.

It is hypothesized that by increasing the removal of biomass, there will be decreases in C and N in the soil surface horizons, and an increase in compaction caused by use of machinery for harvesting and site preparation operations. It is also hypothesized that soil quality indicators like moisture and temperature will be more stable (lower annual variance) near the base of piles/windrows as compared to distance from piles/windrows because of the shadowing effect of piles/windrows. These more stable conditions should be more favorable for microbial decomposition of organic matter thus there should also be higher nutrient availability near the pile/windrow.

Literature Review:

Forests play an important role in ecosystem functions, including carbon sequestration, clean water, wildlife habitat, a renewable source of energy, and wood products. Downed and standing dead woody biomass is an important component of forest ecosystems that can support essential processes such as nutrient cycling, hydrological functioning, soil organic matter maintenance, and habitat for wildlife and soil fauna (Janowiak and Webster, 2010). Woody residue left on site after harvest includes coarse woody debris (CWD) and small or fine woody debris (FWD). CWD includes whole fallen trees and branches (diameter greater than 5 cm), pieces of fragmented wood, stumps, standing dead trees (snags) and logging residues whereas

FWD includes fine roots, twigs and foliage (Mattson et al., 1987; Palviainen et al., 2003; Behjou and Mollabashi, 2013). CWD volume is particularly important as wildlife and soil fauna habitat. It is generally lower in managed forests of the southern US than in the other regions due to intensive site preparation, and a high rate of decay (McMinn and Hardt, 1996). Nevertheless, this coarse woody debris can play an important role in nutrient and moisture retention, nutrient exchange and water dynamics in forested ecosystems (Harmon et al., 1986; Van Lear, 1996). In contrast to CWD, FWD is probably less important as habitat than CWD after harvest because of its rapid decomposition. Its lower lignin content and C:N ratio as well as a greater surface area to volume ratio all contribute to fast decomposition (Palviainen et al., 2003). However, FWD is particularly important to maintaining soil organic matter (OM).

Organic matter (OM) plays an important role in maintaining soil physical and chemical properties, thus affecting plant growth and wildlife habitat. OM provides essential nutrients required for plant growth, moderates soil temperature, moisture and aeration, improves infiltration rates and soil porosity, and acts as a food source for soil organisms, providing a suitable environment for micro, meso and macro fauna (Boyle et al., 1973; Fisher et al., 2000; Vance, 2000). Soil C is a major constituent of soil organic matter and is used as an index for assessing potential changes in site productivity due to management practices (Nave et al., 2010). Nave et al. (2010) found that harvesting had an overall negative to neutral effect on C storage in forests depending upon type of soil, forest, and harvesting operation. Forest floor C losses were significantly higher in hardwoods (-36%) as compared to coniferous or mixed plantations (-20%).

Several studies of whole-tree harvesting conducted in northern hardwoods suggested that due to disturbance caused by harvesting operations, that mixed organic matter from forest floor to the mineral soil led to loss of forest floor C to the upper mineral soil (Mroz et al., 1985; Ryan et al., 1992). Suzanne et al. (2002) found that whole tree harvesting negatively affected forest floor N reserves 15 years after harvesting. A review conducted by Nave et al. (2010) concluded that forest floor C is more susceptible to change following harvest operations than mineral soil. They observed a consistent decline in forest floor C (30±6%) whereas there was no significant change in mineral soil C. Increased soil disturbance due to harvesting and intensive site preparation can cause higher soil C losses (Johansson, 1994; Örlander et al., 1996; Schmidt et al., 1996; Mallik and Hu, 1997).

In addition to the direct impacts of residue removal on nutrient availability and soil physical conditions, residue retention characteristics can indirectly affect ecosystem processes. For example, a study conducted by Roberts et al. (2005) found that residue retention helped reduce competing vegetation regrowth and, as a result soil moisture increased by 1.5% in the third year of growth when compared to treatments where residues were removed. Similarly, in another study O'Connell et al. (2004) found that soil moisture was greater and soil temperature was lower at sites where residue was retained.

Management practices that remove woody biomass residue can also affect soil physical properties, such as accentuation of compaction due to equipment trafficking, but more research is needed to know about temporal patterns as well as effects of these physical changes (Grigal, 2000). Increased trafficking for intensified removal of woody biomass can increase the susceptibility of soil to compaction leading to reduced root growth and penetration due to increased soil strength and decreased macroporosity (Gerard et al. 1982; Soane and Van Ouwerkerk, 1994; Fisher et al., 2000). Akay et al. (2007) found that bulk density increased during residue removal that use rubber-tired skidder, on average, up to values of 1.50 and 2.07 g

cm^{-3} at 10 and 20 cm depth, respectively. Furthermore, with each pass of the skidder (first, fifth, tenth), bulk density increased at 10 cm depth (14, 51,and 61%, respectively) and at 20 cm depth (12, 27,and 32%, respectively), but the use of slash residue over highly disturbed skid trails provided better soil resilience to compaction (Akay et al., 2007). Similarly, Page-Dumroese et al. (2010) showed that leaving harvest residue at the highly trafficked areas can lower soil compaction. Another study by Seixas et al. (1998) found that use of logging residue as trafficking corridors decreased the bulk density by 56%. Therefore, it is essential to study and understand the effects of residue removal on soil conditions before guidelines can be wisely implemented.

In intensively managed forests of the US South, most harvested sites are replanted. Site preparation prior to planting includes several operations that can dramatically alter distribution of woody biomass residues. For example, woody biomass is often piled or windrowed using a tractor or bulldozer mounted blade or rake to allow easy access for bedding or other soil tillage operations. Windrows are long (10-40 m) linear structures that can be 1-5 m high. Piles (sometime referred to as spot piling) may be 5-20 m in length and 2-10 m high. They are generally circular and lack the linear features of windrows but are otherwise similar. Blumfield et al. (2006) conducted a study to determine the effect of residue decomposition on nutrient availability in the top 10 cm of soils between and beneath windrows of different ages for a period of 3 years. They found that total C and N was not significantly different beneath windrows compared to soils at a distance from the windrows. After three years, however, points beneath windrows and near windrows had significantly greater mineralizable N than points at greater distances from the windrow. Mineralizable N was 1-2% higher in the third year after the harvest at and near windrow points but there was not any significant differences detected in first and second year. Also, $^{13}C\%$ was significantly lower near windrows than far from windrow indicating movement of labile C into the soils beneath windrows by third year (Blumfield et al., 2006).

Patterson et al. (2002) studied soil profile characteristics of windrowed loblolly pine plantations and found surface and sub-surface bulk density values were greater in areas far from windrows (1.53±0.02 and 1.67±0.03, respectively) than in areas near and beneath windrows (1.18±0.04 and 1.51±0.04, respectively). There was no significant difference in OM or K concentration near to windrow than far from windrows, but site index (SI) was higher in windrowed plots than in non-windrowed plots (97.2 ft) and published soil survey SI (Patterson et al., 2002). Gent and Morris (1986) evaluated the influence of harvesting and pre-plant site preparation that included windrowing on soil physical properties of an Upper Coastal Plain site. In the sandy loam soils they studied, harvest significantly increased bulk density in both skid trail and non-skid trail areas. However, no difference in bulk density, aeration porosity or saturated hydraulic conductivity were observed between areas prepared for planting by windrowing and those prepared for planting by roller drum chopping.

While the literature review establishes that there are general benefits of retaining some residues on harvested forest sites, there is a paucity of information on the quantity that should be retained to protect ecosystem functions. This is particularly true of the US South, where plantation management has been the norm for more than fifty years. The relatively low CWD mass of managed plantations coupled with high decomposition rates make it difficult to extend results of studies completed in other regions. Moreover, it is in the South where demand for bioenergy production is the greatest.

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CHAPTER II

Woody Biomass Residue Retention Effects on Soil Quality Indicators in the Lower Coastal Plain Soils of Georgia

[1]Anchal Bangar, Daniel Markewitz, and Lawrence Morris. To be sumbitted to Biomass and Bioenergy.

Abstract

Residual biomass remaining after commercial timber harvest in pine plantations of the southeastern USA is a significant source of biomass for bioenergy. Removal of these woody residues has the potential to negatively affect soil quality and site productivity. The objective of this study was to determine the effect of residual woody biomass harvesting on soil quality indicators at Lower Coastal Plain sites in Rincon and Brunswick, Georgia. A total of four replicates of six treatments were established based on the percentage of operationally accessible residual biomass left after harvest (100, 30, 15, or 0%) and whether the biomass was left in a clustered or dispersed distribution. Pre-harvest and post-site preparation sampling of forest floor (Oi, Oe+Oa) and mineral soil (0-15 cm depth) measured forest floor mass, total soil organic carbon (SOC) and nitrogen concentrations. Bulk density was sampled to evaluate the effect of harvesting and site-preparation on soil compaction. Forest floor mass varied significantly between pre-harvest and post-site preparation ($p<0.0001$) and among the six biomass harvesting treatments ($F= 1$, $p=0.009$). When averaged across treatments, the post-site preparation forest floor mass decreased by 54.4% (9.28 Mg ha^{-1}) as compared to pre-harvest forest floor. C concentration in the forest floor also differed post-site preparation ($F=109.89$, $p=0.0001$). There was a significant increase of 14.5% (to 1.41 g cm^{-3}) in bulk density following harvest and site-preparation when averaged across treatments ($p<.0001$). Biomass harvesting treatments did not have any significant effect on soil bulk density. Similarly, there was a significant increase in total mineral soil organic carbon (SOC) content by 56% (or 15.45 Mg ha^{-1}) after harvesting and site preparation but SOC didn't differ among residue retention treatments. Residue harvesting treatments clearly altered the mass of forest floor but impacts on bulk density or SOC were not detectable.

Introduction

The rising costs and social concerns over fossil fuel extraction and combustion have resulted in increased interest in and opportunities for bioenergy. Biomass in the form of coarse woody residues remaining after timber harvest in pine plantations of the southeastern USA is a significant potential source of biomass for bioenergy. The Southeast and south-central United States are estimated to contribute 32 million Mg out of a total 57 million Mg of dry residue produced at the national level (Milbrant, 2005).

Removal of these woody residues however, has the potential to negatively affect soil quality and therefore soil productivity (Scott and Dean; 2006, Eisenbies et al., 2009). Therefore, it is essential to understand the effect of removal of this biomass residue on soil attributes that control its productivity. Indices of soil quality attempt to capture these attributes. Soil quality depends on the ability of soil to provide adequate soil water and drainage, cycle essential nutrients, and provide a medium that promotes root growth and essential soil habitat for meso- and micro-fauna, and micro-flora (Burger et al., 2010). Effect of woody biomass removal on soil quality can be estimated by quantifying soil properties that may be most vulnerable to disturbance caused by harvesting or site preparation operations. Soil nutrients and soil moisture are limiting factors for pine plantations grown and soil attributes related to these components include soil C and N, and bulk density (Fox et al., 2007).

Soil C is a major constituent of soil organic matter and is used as an index for assessing potential changes in site productivity due to management practices (Nave et al., 2010). Nave et al. (2010) found that harvesting had an overall negative to neutral effect on C storage in forests depending upon type of soil, forest, and harvesting operation. Nave et al. (2010) found that generally C losses were higher in hardwoods (-36%) when compared with coniferous/mixed stands (-20%). Another review conducted by Johnson and Curtis (2001) found that over a period of 15-16 years, harvesting had little or no effect on soil C and N but results varied depending upon the type of harvest and tree species. In a comparison of sawlog only vs. whole tree harvesting (i.e. including all branches and tops), saw log harvesting caused an 18% increase in soil C and N whereas whole tree harvesting had a negative effect (-6%). Several studies of whole-tree harvesting conducted in northern hardwoods suggest that disturbance by harvesting operations that mixed organic matter from forest floor to the mineral soil leading to loss of forest floor C to the upper mineral soil (Mroz et al., 1985; Ryan et al., 1992). The study conducted by Nave et al (2010) showed that forest floor C is more susceptible to change following harvest operations. They observed consistent decline in forest floor C storage (30±6%) whereas there was no significant change in mineral soil C storage. However, other studies found that increased soil disturbance due to harvesting and intensive site preparation can also cause soil C loss. (Johansson, 1994; Örlander et al., 1996; Schmidt et al., 1996; Mallik and Hu, 1997).

Soil compaction is a physical form of degradation that can change the soil structure as the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby, increasing the bulk density (SSSA 1996; Mueller et al. 2010). Increased trafficking for the intensified removal of woody biomass can greatly increase soil compaction. Increased compaction can lead to reduced root growth and root penetration due to increased soil strength and a decreased number of macropores potentially resulting in a loss of site productivity (Gerard et al. 1982; Soane and Van Ouwerkerk, 1994; Fisher et al., 2000). Various studies have reported that organic matter retention results in improved soil physical properties like reduced soil compactability and increased stability under wet conditions (Soane, 1990; Ball et al., 2000;

Golchin et al., 1995; Dexter, 2004a; Dexter, 2004b; Dexter, 2004c). Compaction by machinery during harvesting operations and organic matter removal can affect the porosity of soil (Bruand and Cousin, 1995; Richard et al., 2001; Dexter et al., 2008).

Bulk density is calculated as dry soil mass per unit volume and is most commonly used as a measure of soil compaction (Panayiotopoulos et al. 1994). Many studies have shown that soil compaction is a common problem resulting from forest harvest. For instance, Solgi and Najafi (2014) found that bulk density was 57% higher in the surface layer (0-10cm) of skid trails as compared to undisturbed area (i.e. intact forest floor). Total porosity was 31% lower and moisture content was 12 % lower in the disturbed skid trail when compared to intact forest floor area (Solgi and Najafi, 2014). Similarly, Akay et al. (2007) found that bulk density increased during the use of a rubber tired skidder, on average, to 1.50 and 2.07 g cm^{-3} at 10 and 20 cm depths, respectively. Furthermore, with each pass of the skidder (first, fifth, tenth), bulk density increased at 10 cm (14, 51, and 61%, respectively) and at 20 cm depth (12, 27, and 32%, respectively). These investigations showed that the use of slash residue over highly disturbed skid trails provided better soil resilience to compaction (Akay et al., 2007). In general, leaving harvest residue at highly trafficked areas can lower soil compaction (Page-Dumroese et al., 2010). Seixas et al (1998) found that use of logging residue decreased bulk density increases by 56%.

The above studies largely investigated the impacts of final harvests on soil attributes with some variation in harvest intensity (e.g., sawlog only vs whole tree). The main objectives of this study, however, are to specifically evaluate soil attributes under varying rates of woody residue retention during harvest. In the study region, harvest of pine plantations often includes removal of woody residues that are accessible such as material piled at a delimbing gate. In this study retention rates of 15 or 30% of woody residue were experimentally imposed and compared to no residue harvest or the current woody residue harvesting practices. Specific objectives of the study are to 1) quantify the effect of different levels of biomass harvesting on forest floor and mineral soil carbon and nitrogen, and 2) quantify the effect of harvesting and site preparation operations on bulk density. It is hypothesized that by increasing the removal of biomass, there will be decreases in C and N in forest floor and mineral soil surface horizons. It is also hypothesized that higher rates of woody residue removal will increase compaction caused by use of machinery for harvesting and site preparation operations.

Materials and Methods

Study areas and experimental design

The study was conducted in Coastal Plain locations near Rincon and Brunswick, Georgia. Four replicate blocks were installed (three at Brunswick and one at Rincon) in a randomized complete block design. Each replicate block of approximately 48 ha was divided into six different treatments based on the amount of residual harvestable biomass retention and distribution of the residue. Residue distribution focused specifically on wildlife communities (i.e., small mammals, herptofauna, etc.) and whether piling residues into clusters after some level of additional harvest removal may improve habitat. Results specific to wildlife were reported earlier (Farrell, 2013), while here the focus is on impacts on soil attributes, which are relevant as more equipment activity is required to cluster residues. The six different treatments were:

- 100 RET: Tree stem wood harvest with no residual biomass harvest.

- 30RETCLUS: 30% of operationally harvestable biomass residue retained in a clustered distribution;
- 30RETDISP: 30% of operationally harvestable biomass residue retained in a dispersed distribution;
- 15RETCLUS: 15% of operationally harvestable biomass residue retained in a clustered distribution;
- 15RETDISP: 15% of operationally harvestable biomass residue retained in a dispersed distribution,
- '0' RET: Removal of all operationally (economically) harvestable biomass residues (No Biomass Harvesting Guidelines);

In this study, operationally harvestable biomass included CWD and standing biomass that was selected for removal by a contractor that regularly harvest biomass for electric power generation. Generally, it did not include stems less than 5 cm in diameter unless they were part of a pile nor did it include all larger stems when they were widely dispersed on the site. Fine woody debris (FWD) was not generally harvested.

Each treatment plot of 8-10 ha had six randomly selected sub-plots established for sampling. The study sites were dominated by Bladen loam (Bk), Bladen fine sandy loam (BdA) {Fine, mixed, semiactive, thermic Typic Albaquults}, and Rains fine sandy loam (Ra) {Fine-loamy, siliceous, semiactive, thermic Typic Paleaquults} soil series. These soils are poorly drained which necessitates bedding the site prior to planting.

Study sites in Georgia are currently managed by Plum Creek Timber Company, Inc. for commercial timber production. Study stands were initially harvested at the age of 25-33 years.

During harvesting, all residue material in 15 or 30% of the area in the retention plots (15Retclus, 15Retdisp, 30Retclus, 30Retdisp) was left in place and this material was then distributed in a dispersed or clustered pattern across the treatment plot. After harvest and residue treatments, plots were site prepared for planting by shearing with a KG Blade and bedding. These site preparation practices left much of the woody residue in the form of windrows. Sampling was concentrated in the inter-bed area to focus on the effects of residue removal on soils and not on operational bedding. Three of the four replicates received a banded herbicide treatment followed by mechanical site preparations including shearing and piling and planting was done at 1.8*3.7 m spacing (1495 trees/ha). One replicate received broadcast herbicide treatment and planting was done at 1.5*3.7 m spacing (1,794 trees/ha). Pre-harvest samples at all four replicates were collected in early spring 2011 while post-site preparation samples were collected in late fall 2011 and mid-winter 2012.

Sample collection

Coarse-woody debris (CWD) volumes were estimated from measurements collected in the late fall to mid-winter at six sub-plots in each treatment plot. Any woody debris with diameter ≥5-cm was categorized as coarse-woody debris (CWD). A modified line-intersect sampling technique was used to estimate CWD volume and mass. The large end diameter and length of CWD that intersected two 7.62-m transect lines from the center of the sub-plots oriented on 180°S and 270°W azimuths were recorded (Marshall et al., 2000).

Forest floor samples were collected at each subplot using a 39*39 cm aluminum sampling frame with an area of $0.15m^2$. Samples were separated into small woody debris (FWD, diameter<5cm), Oi (fresh litter layer) and Oe+Oa (organic matter, decomposed) horizon and stored in kraft paper bags (Forest Inventory and Analysis, 2011).

After removing and collecting forest floor samples, mineral soil samples were obtained by using an Oakfield probe at 6-8 spots within the frame and compositing into a single sample. Composite mineral soil samples were stored in paper bags (FIA, 2011).

Pre-harvest and post-site preparation bulk density samples were collected in early spring 2011 and late fall 2011to early winter 2012, respectively. Bulk density samples were collected from each sub-plot using a 7.5 cm diameter by 7.5 cm height core cylinder and slide hammer (Sheldrick, 1984).

Sample processing and analysis

A total of 720 soil samples (5 samples* 6 sub-plots* 6 treatments* 4 blocks) were returned to the laboratory at Whitehall Forest in Athens, GA for further processing. Forest floor samples were oven-dried at 70°C to a constant weight, weighed to 0.10 g, and ground through a Wiley mill using 2 mm mesh screen. Composite mineral soil samples were air-dried, lightly crushed, and sieved using a 2mm mesh screen. A SPEX 8000 ball mill grinder (Spex SamplePrep, LLC, Metuchen, NJ) was used to grind 2g of each forest floor and mineral soil sample to a fine powder.

For total C and total N analysis, ~10 mg of ball mill ground forest floor sub-samples and ~100 mg of ball mill ground mineral soil sub-samples were weighed into tin capsules. The sub-samples were then analyzed using a CHN Element Analyzer- NC 2100 (CE Instruments, CE Elantech Inc., Lakewood, NJ).

Bulk density samples were oven dried at 105°C until a constant weight (Sheldrick, 1984). Samples were sieved for roots and rocks and volume and mass corrections were made as necessary.

Statistical analysis

Following the completely randomized block design with four complete blocks, Analysis of Variance was utilized to test for treatment effects. PROC GLM procedure (Proc GLM, Statistical Analysis Systems software, version 9.3; SAS Institute Inc. 2010, Cary, NC) was used to identify and interpret statistically significant differences at $p < 0.05$. Both pre-harvest and post-site preparation and treatment effects were tested. Mean values from the six measurement sub-plots within each treatment within each block were used to evaluate differences among biomass retention treatments. Analysis of variance (ANOVA) was also used to evaluate the statistical significance of treatment by block interactions. For statistical analysis, PROC ANOVA within SAS version 9.3 was used.

Results

Forest Floor

Total forest floor mass (i.e., Oi + Oe+ Oa+ FWD) differed significantly between pre harvest and post site preparation measurements ($F=23.96$, $p<0.0001$; Table 2.1). Forest floor mass also differed significantly among the six biomass harvesting treatments ($F= 1.91$, p=0.00938). Averaged across treatments, the post site preparation forest floor mass decreased by 54.4% (or 9.28 Mg ha^{-1}) as compared to pre-harvest forest floor (Table 2.2). Mass of the Oe+Oa horizon decreased by 76% (or 6.58 Mg ha^{-1}) and in the Oi horizon, there was a decrease of 71% (or 4.89 Mg ha^{-1}) (Table 2.2). Unlike Oi and Oe+Oa horizons, there was an increase of 2.2 Mg ha^{-1} in FWD post site preparation (Table 2.2).

Pre-harvest C concentration in all forest floor fractions was significantly different as compared to post site preparation (F=109.89, p=0.0001) (Table 2.1). However there was no significant treatment effect (F=0.84, p=0.5712). When averaged across treatments, the decrease in C concentration in Oe+Oa horizon after post site preparation was 57% (or 195.48 g kg^{-1}) (Table 2.2). Due to the observed decrease in forest floor mass (Oi and Oe+Oa) after harvesting and site preparation, a decrease in C content was expected independent of changes in concentration. There was a decrease in average C content in Oi and Oe+Oa fractions by 84.3% (or 2.57 Mg ha^{-1}) after post-harvest and site preparation (Table 2.2). C content in FWD, however, increased by 53.8% (or 0.75 Mg ha^{-1}) (Table 2.2).

Pre-harvest N concentration in forest floor differed significantly from post site preparation N concentration (F=26.13, p=0.0037) (Table 2.1.). However, no significant treatment effect was found (F=1.68, p=0.2916). After site preparation, there was a decrease in N concentration in all three forest floor horizons when averaged across treatments but this was not significant. The largest decrease in N concentration was observed in Oe+Oa horizon (a decline of 5.18 g kg^{-1} or a 58% decrease) as compared to Oi (1.12 g kg^{-1} decline) and FWD horizon (0.16 g kg^{-1} decline) (Table 2.3). As there was a significant decrease in forest floor biomass after harvesting and site preparation, N content decreased in all the Oi and Oe+Oa horizons by 78.2 to

85.8% (0.04 to 0.07 Mg ha^{-1}) (Table 2.3). N content in FWD, however, increased by 60.6% (0.01 Mg ha^{-1}) due to an increase in FWD biomass post-harvest (Table 2.3).

Mineral Soil

There was a significant difference in bulk density between pre-harvest and post site preparation soil (F=56.89, p<.0001). Treatment did not, however, have any significant effect on bulk density before harvest or post site preparation (F=2.03, p=.0748). There was an effect of trafficking during harvest and site preparation on soil compaction as bulk density increased by 14.5% to an average value of 1.41 g cm^{-3} following harvest and site preparation when averaged across treatments (Table 2.4).

Similarly, there was a significant difference in total soil organic carbon (SOC) concentration between pre-harvest and post site preparation soil (F=19.03, p=.0004) but different harvesting treatments did not have any significant effect (F=1.51, p=0.2365) (Table 2.1 and 2.5). Total SOC concentration increased significantly by 34% (or 5.16 g kg^{-1}) after harvesting and site preparation (Table 2.5) when averaged across treatments. Total SOC content increased by 56% (or 15.45 Mg ha^{-1}) after harvesting and site preparation (Table 2.5).

Total mineral soil N concentration varied significantly from pre-harvest to post site preparation treatment (F=15.35, p=0.0010) whereas no significant differences were found among the six different harvesting treatments (F=1.20, p=0.3467) (Table 2.1). When averaged across treatments, total soil N concentration increased significantly by 42% (0.27 g kg^{-1}) after harvesting and site preparation (Table 2.5). Total soil N content increased by 66% (0.77 Mg ha^{-1}) on average across the six treatments post site preparation (Table 2.5).

Discussion

The effects of forest harvest and biomass removal on soil condition and site productivity have been studied over many decades (Scott and Dean, 2006; Eisenbies et al., 2009; Tullus et al., 2012; Berger et al., 2013). During the 1970's when whole tree harvesting was proposed to increase woody biomass removal for energy production, a range of studies were initiated focussing specifically on increased biomass removal (Kimmins, 1977; Van Hook et al., 1980). Currently, the extent of biomass removal has again expanded to consider woody residuals left in the site after tree removal. In response some states have proposed guidelines for retention of woody residuals (Abbas et al., 2011).

These guidelines, as proposed by different states, focus on dead woody material left on site after harvesting. For example, Michigan's guidelines recommend leaving one-sixth to one-third of the woody material less than 4 inches diameter on site. Wisconsin's guidelines recommend leaving all the pre-harvest dead woody material and tops and limbs from10 percent of the trees on site (at least 5 tons of fine woody material per acre), and leaving extra material in forest areas which lack dead woody material (Evans et al., 2010). Leaving 15-30 percent of the harvestable biomass is suggested in Pennsylvania's guidelines and Missouri's guidelines suggest retaining 33 percent of the harvest residue. Most of these states except Michigan and Missouri suggest leaving all snags (standing dead/dying tree) possible at the harvest site (Evans et al., 2010).

The main issue with the existing biomass harvesting guidelines is the lack of empirical evidence for the recommendations; therefore, there is a need to develop guidelines that should be science based rather than simply following guidelines previously recommended in another state. Biomass is a very general term and therefore specific guidelines need to be formed for retention levels of coarse or fine woody debris depending upon their effect on soil quality. The current study is unique in being specifically designed to address different levels of woody biomass retention and separating these from impacts of harvest and site preparation.

In this study, there were significant decreases in total C and N concentration and content following harvest and site preparation in the forest floor (Table 2.1). On average across all treatments, the post-harvest and site preparation C and N concentration in forest floor mass decreased by 16-57 and 3-58 %, respectively. The decline in forest floor C can be due to the fragmentation and mixing of organic matter by harvesting and site-preparation equipment which accelerates decomposition losses. Leaching or eluviation of C to the mineral soils beneath the forest floor may also increase. Similar results have been observed in a review by Nave et al. (2010) that demonstrated a relatively consistent 30 % decline in forest floor C storage across a range of forest (coniferous/mixed and hardwood stands) and soil types after harvest.

Response in mineral soils following harvest and site preparation differed from forest floor in that soil C concentration increased by 34%. This increase can be explained by movement of forest floor C to the mineral soil due to mixing during harvest and site preparation or incorporation through bioturbation after decomposition (Covington et al., 1994; Yanai et al., 2003). Bulk density also increased by 14.5% from an average value of 1.21 to 1.41g cm^{-3}, which can be another reason for an increase in soil C after harvesting and site preparation. Total soil N concentration also increased by 42%.

These impacts of forest harvests on soil attributes have been previously observed and can vary across studies. The review of Johnson and Curtis (2001) combined results from 26 studies and found that in coniferous species, sawlog harvest increased soil C and N by an average of 18%. A meta-analysis study by Nave et al. (2010) found that in general, there was a harvest induced 30±6% decrease in forest floor C but found no significant change in mineral soil C. These past results, however, reflect forest harvest and do not specifically address the extent of residual biomass removal.

Among the six biomass residue retention treatments, bulk density and total soil C and N concentration differences were not significant. It can be challenging to detect significant differences among these treatment plots due to high variability in soil conditions, drainage, and harvest operations. In this study, to address issues of variability, 720 samples were collected at each site with 120 samples for a treatment based on 30 samples within a specific treatment plot and n=4 replicate plots. Given the standard error estimates for the various attributes (Table 2.2-2.5) and an ability to pool across location (i.e., n=4 blocks or plots) then a difference of 30-40% in any attribute would have been detected with an α=0.1. A smaller difference of 10%, for example, in forest floor or mineral soil C contents would be an absolute difference of ~200-300 kg-C and would not be detectable.

In addition to the challenges of spatial variance, aspects of temporal variance are also important. Previous studies of residue removal, such as Jones et al. (2011), have found significant differences in soil C and N concentration among the forest floor+residue removal and stem only harvest treatments in 0-10 cm depth mineral soil. However, the post-harvest sampling by Jones et al. (2011) was done at mid-rotation (15 years after planting) whereas in the current study, post-harvest sampling was done within a few months after planting. In a study three years after harvest, Johnson et al (2001) found no significant differences in soil C among sawlog and whole tree harvest treatments on sites in Tennessee but in a North Carolina site there was an increase in soil C of 57% in the top 10 cm soil layer. Other studies ranging over periods of 4 to 14 years comparing whole tree harvest and conventional harvesting were similar to the current study in finding no significant differences in site productivity between these treatments (Sanchez et al., 2006; Roxby and Howard., 2013).

The previous studies as well as the current study suggest that levels of woody residue harvest or retention, such as the 15 or 30% retention used here, may not measurally impact soil C and N pools at 0-15 cm depth and in this sense, this study mirrors results of previous studies of complete, whole tree or operational residue removal harvests. The large operational plots in this study, in fact, demonstrated that residue removal of fine woody debris is difficult and costly. As such, even under the no biomass harvesting guideline treatment ('0' RET), substantial organic material is left on site. Briedis et al. (2011) found that due to mechanical limitations, there was an average of 45% of harvested residue and 15% of harvested woody material (round wood and energy wood) retention in their whole tree harvest treatment plots. As such, all levels of operational woody biomass residue removal may leave sufficient material on site to sustain soil quality and site productivity.

The pine forests utilized in this study also represent lands that are often recovering from a history of agricultural activity (Richter and Markewitz, 2001) and may be in a second or third rotation of pine management. As such these lands have been retained in an early succession stage and have accumulated limited amounts of coarse woody debris. Furthermore, these plantations are often managed with fertilizers that might help ameliorate nutrient losses from increased residue harvest.

Conclusion:

Harvest of woody biomass residues can affect many aspects of the forest ecosystem such as soil, water, biodiversity, etc. The potential impacts will vary based on the forest ecosystem and soils, as well as the operational activities undertaken. This study found declines in forest floor C and N contents and some increases in soil bulk density and mineral soil C contents but these responses were evident relative to pre- and post-harvest comparison. Differences in soil attributes in relation to levels of woody biomass residue retention were not detected. Given that woody residue removal even under treatments with no biomass harvesting guidelines is incomplete, removals may not be sufficient to limit carbon and nutrient recycling to negatively impact soil productivity.

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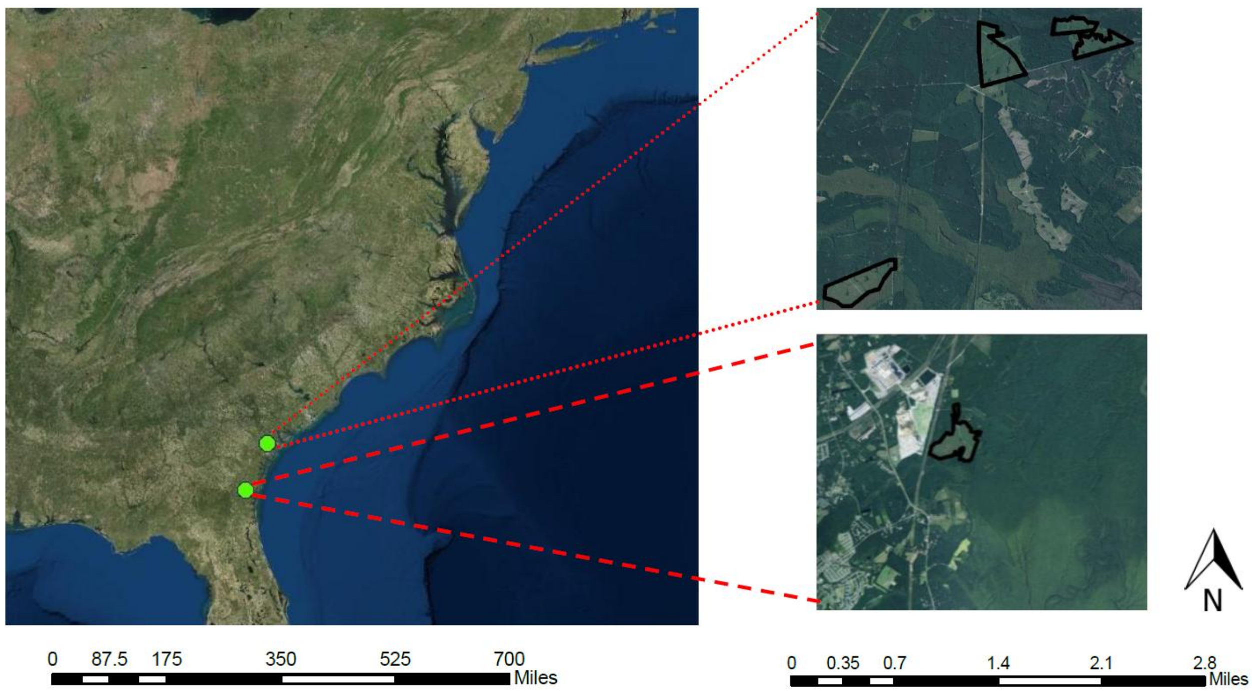

Figure 2.1. Map of the Biomass Harvesting Guideline study area showing the location of the four replicate blocks in Glynn (three replicate blocks) and Effingham County (one replicate block), Georgia.

Table 2.1. Statistical summary (probability>F) of biomass residue retention (No guidelines, 15, 30, or 100% retention) and harvest (pre- and post-) effects on total nitrogen and carbon concentrations of the forest floor and 0-15 cm mineral soil. Samples were collected from three blocks in Brunswick and one block in Rincon in the Coastal Plain of Georgia in 2011/2012.

Effects	**Total Carbon**	**Total Nitrogen**
	---------- % ----------	
	----------------------Forest Floor--------------------	
	------------------Oi------------------	
Residue Retention	0.6212	0.3234
Harvest	**<.0001**	0.0692
	--------------*Oe+Oa*------------------	
Residue Retention	0.4382	0.1095
Harvest	**0.0008**	**<.0001**
	-----------------*FWD*----------------	
Residue Retention	0.5468	0.4735
Harvest	**0.0014**	0.8421
	-------*Oi + (Oe+Oa) + FWD*-------	
Residue Retention	0.5712	0.2916
Harvest	**0.0001**	**0.0037**
	---------------------Mineral Soil----------------------	
Residue Retention	0.2365	0.3467
Harvest	**0.0004**	**0.001**

Table 2.2. Pre-harvest and post-site preparation average mass and total carbon concentration and content of the forest floor (Oi, Oe+Oa, and FWD horizon) at Rincon (one replicate) and Brunswick (three replicates), Georgia across four replicate blocks. Samples were collected in 2011/2012.

Residue Retention Treatment*	**Total C Concentration**		**Mass**		**Total C Content**	
	Pre-harvest	**Post-site Prep.**	**Pre-harvest**	**Post-site Prep.**	**Pre-harvest**	**Post-site Prep.**
	----------------- g kg^{-1} --------------		--------- Mg ha^{-1} ---------		-------- Mg ha^{-1} ---------	
			Oi			
100 RET	451.8 (10.6)	288.5 (39.5)	6.98 (2.31)	1.62 (0.77)	3.15	0.47
30RETCLUS	457.9 (13.7)	249.7 (26.4)	7.36 (2.48)	0.81 (0.41)	3.37	0.20
30RETDISP	465.8 (5.5)	287.1 (25.7)	7.34 (1.76)	2.24 (1.24)	3.42	0.64
15RETCLUS	451.3 (10.7)	316.1 (47.9)	4.47 (0.63)	0.72 (0.39)	2.02	0.23
15RETDISP	461.8 (8.8)	310.2 (44.0)	6.95 (2.14)	2.26 (1.24)	3.21	0.70
'0' RET	450.8 (4.6)	313.5 (53.7)	5.57 (0.68)	1.67 (0.65)	2.51	0.52
			Oe+Oa			
100 RET	349.9 (18.1)	146.7 (93.0)	9.46 (1.99)	4.09 (4.09)	3.31	0.59
30RETCLUS	363.9 (42.9)	75.9 (75.9)	7.94 (1.45)	0.81 (0.81)	2.88	0.06
30RETDISP	360.1 (28.5)	223.0 (95.9)	10.29 (1.46)	1.39 (0.55)	3.71	0.31
15RETCLUS	322.4 (13.3)	117.3 (67.7)	7.88 (2.61)	0.51 (0.39)	2.54	0.06
15RETDISP	331.1 (15.9)	224.7 (76.5)	10.09 (2.13)	8.47 (4.10)	3.34	1.90
'0' RET	320.2 (19.1)	87.4 (87.4)	9.72 (2.59)	0.59 (0.59)	3.11	0.052
			FWD			
100 RET	466.5 (3.3)	397.7 (16.0)	1.47 (0.35)	4.76 (2.65)	0.69	1.89
30RETCLUS	468.3 (4.0)	336.6 (29.6)	1.54 (0.30)	3.73 (2.26)	0.72	1.26
30RETDISP	462.3 (8.1)	412.4 (13.7)	1.31 (0.25)	4.31 (1.87)	0.60	1.78
15RETCLUS	471.9 (3.9)	398.3 (14.6)	1.42 (0.39)	2.60 (0.82)	0.67	1.04
15RETDISP	468.7 (11.9)	386.8 (18.1)	1.39 (0.11)	3.38 (1.75)	0.65	1.31
'0' RET	468.4 (6.7)	413.3 (14.2)	1.13 (0.18)	2.69 (1.47)	0.53	1.11

† Numbers in parentheses indicate the standard error (SE), where n=4 for each treatment.

* 100 RET= no residue woody biomass removed, '0' RET= operationally feasible residue woody biomass removed, RETCLUS= woody biomass retained (15 or 30%) on site in clustered distribution and RETDISP= residue woody biomass retained (15 or 30%) in dispersed pattern.

Table 2.3. Pre-harvest and post-site preparation total nitrogen concentration and content of the forest floor (Oi, Oe+Oa, and FWD) at Rincon (one replicate) and Brunswick (three replicates), Georgia across four replicate blocks. Samples were collected in 2011/2012.

Residue Retention Treatment*	**Total N Concentration**		**Total N Content**	
	Pre-harvest	**Post-site Prep.**	**Pre-harvest**	**Post-site Prep.**
	---------------- g kg^{-1} -----------------		-------- Mg ha^{-1} ---------	
		Oi		
100 RET	7.50 (0.58)	7.29 (1.29)	0.052	0.019
30RETCLUS	7.30 (1.15)	4.17 (1.94)	0.054	0.003
30RETDISP	7.66 (0.85)	7.70 (0.39)	0.056	0.017
15RETCLUS	8.16 (0.71)	6.32 (1.10)	0.037	0.005
15RETDISP	8.01 (1.14)	7.47 (1.55)	0.056	0.017
'0' RET	7.50 (0.53)	6.46 (0.96)	0.042	0.011
		Oe+Oa		
100 RET	9.10 (0.56)	2.91 (2.20)	0.086	0.012
30RETCLUS	9.55 (0.80)	4.17 (4.17)	0.076	0.003
30RETDISP	8.80 (0.47)	4.49 (2.09)	0.090	0.006
15RETCLUS	8.92 (0.84)	2.84 (1.67)	0.070	0.002
15RETDISP	9.74 (0.64)	5.46 (2.28)	0.098	0.046
'0' RET	7.95 (0.62)	3.10 (3.10)	0.077	0.002
		FWD		
100 RET	4.76 (0.53)	4.90 (0.51)	0.007	0.023
30RETCLUS	4.66 (0.58)	3.17 (2.02)	0.007	0.012
30RETDISP	5.39 (0.51)	5.11 (0.98)	0.007	0.022
15RETCLUS	5.70 (0.74)	4.68 (0.90)	0.008	0.012
15RETDISP	4.98 (0.46)	8.29 (2.94)	0.007	0.028
'0' RET	5.11 (0.39)	3.51 (1.01)	0.006	0.009

† Numbers in parentheses indicate the standard error (SE), where n=4 for each treatment.

* 100 RET= no residue woody biomass removed; '0' RET=operationally feasible residue woody biomass removed; RETCLUS= woody biomass retained (15 or 30%) on site in clustered distribution; and RETDISP= residue woody biomass retained (15 or 30%) in dispersed pattern.

Table 2.4. Pre-harvest and post-site preparation mean soil bulk density (between 0-15cm depth) by BHG treatment designation for Rincon (one replicate) and Brunswick (three replicates), Georgia across four replicate blocks. Samples were collected in 2011/2012. Samples were collected in 2011/2012.

	Residue Retention Treatment*	Block 5**	Block 6	Block 7	Block 8	Mean Bulk Density
		------------------------------ $g\ cm^{-3}$			------------------------------	------- $g\ cm^{-3}$ -------
Pre-harvest	100 RET	1.16	1.09	1.42	1.27	1.23 (0.07)
	30RETCLUS	1.11	1.21	1.54	1.18	1.26 (0.10)
	30RETDISP	1.50	1.16	1.38	1.20	1.31 (0.08)
	15RETCLUS	1.21	0.89	1.22	1.26	1.14 (0.09)
	15RETDISP	1.28	0.95	0.96	1.19	1.09 (0.08)
	'0' RET	1.24	1.00	1.38	1.17	1.20 (0.08)
Post-site prep	100 RET	1.33	1.35	1.59	1.47	1.43 (0.06)
	30RETCLUS	1.38	1.23	1.51	1.43	1.38 (0.06)
	30RETDISP	1.23	1.25	1.91	1.42	1.45 (0.16)
	15RETCLUS	1.33	1.33	1.49	1.54	1.42 (0.06)
	15RETDISP	1.25	1.20	1.59	1.41	1.36 (0.09)
	'0' RET	1.37	1.37	1.53	1.35	1.41 (0.04)

† Numbers in parentheses indicate the standard error (SE), where n=4 for each treatment.

* 100 RET= no residue woody biomass removed; '0' RET=operationally feasible residue woody biomass removed; RETCLUS= woody biomass retained (15 or 30%) on site in clustered distribution; and RETDISP= residue woody biomass retained (15 or 30%) in dispersed pattern.

**Blocks 1-4 are in North Carolina and not included in this manuscript.

Table 2.5. Pre-harvest and post-site preparation total nitrogen and total carbon concentration and content of the mineral soil (0 - 15 cm depth) by treatment designation for four Georgia replicate blocks in Rincon (one replicate) and Brunswick (three replicates), Georgia. Samples were collected in 2011/2012.

	Treatment*	Total Concentration		Total Content	
		Pre-harvest	Post-site prep.	Pre-harvest	Post-site Prep.
		----------------- g kg^{-1} -------------		-------- Mg ha^{-1} ---------	
Total Nitrogen	100 RET	0.61 (0.11)	0.74 (0.20)	1.13	1.60
	30RETCLUS	0.76 (0.12)	0.75 (0.06)	1.39	1.68
	30RETDISP	0.59 (0.04)	0.97 (0.06)	1.19	1.96
	15RETCLUS	0.65 (0.12)	0.94 (0.23)	1.03	1.99
	15RETDISP	0.73 (0.19)	1.16 (0.42)	1.28	2.39
	'0' RET	0.51 (0.02)	0.91 (0.21)	0.91	1.92
Total Carbon	100 RET	14.42 (2.00)	17.74 (1.50)	26.68	38.19
	30RETCLUS	18.47 (3.35)	19.24 (3.44)	33.65	43.01
	30RETDISP	14.41 (1.67)	21.14 (2.45)	29.36	42.73
	15RETCLUS	15.17 (1.82)	18.15 (4.04)	24.16	38.48
	15RETDISP	16.05 (2.60)	24.97 (6.69)	28.29	51.33
	'0' RET	12.27 (0.95)	20.49 (2.85)	22.08	43.20

† Numbers in parentheses indicate the standard error (SE), where n=4 for each treatment.

* 100 RET= no residue woody biomass removed; '0' RET=operationally feasible residue woody biomass removed; RETCLUS= woody biomass retained (15 or 30%) on site in clustered distribution; and RETDISP= residue woody biomass retained (15 or 30%) in dispersed pattern.

CHAPTER III

Windrow and Pile Size Effects on Soil Quality Indicators in the Lower Coastal Plain of Georgia and North Carolina

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Abstract

An increase in residual woody biomass removal for bioenergy production has led to proposed guidelines for the extent of residual harvesting. These proposals, however, do not address how site preparation reconfigures these residuals into windrows or piles of various sizes. Increased residual removal may impact the average size of such windrows or piles, which may in turn impact soil attributes. As such, the objective of this study was to determine the effect of residual biomass windrow (in Georgia) or pile (in North Carolina) sizes on surrounding soil properties. Soils were measured at 0-15 cm depth with distance from small, medium, or large windrows/piles for total soil organic C (SOC), total soil N, exchangeable Ca, Mg, K, and PO_4-P. In addition, soil moisture, soil temperature, and soil respiration were measured from July 2012 to August 2013. SOC and N concentration did not vary significantly with windrow size or distance from the windrow. Mineral soil extracts showed that neither size nor distance from the windrow/pile had any significant effect on exchangeable Ca, Mg, K, or PO_4-P in North Carolina whereas, in Georgia, K decreased with distance. Ion-exchange resin extracts showed similar results in North Carolina except K varied significantly with distance and followed a declining pattern. In Georgia, resin extractable Mg and K decreased significantly with distance from the windrow. Windrow size had a significant effect with large windrows having higher exchangeable K. Distance from the windrow had a significant effect on soil moisture and temperature but pile size effects were non-significant. Generally, temperature near the windrow was lower than points farther from the windrow but this pattern was limited to a meter distance. Soil respiration was neither affected by distance from the windrow nor windrow size. Overall, these results suggest that reconfiguring woody residues into large windrows/piles may have some effect on K or temperature but impacts are restricted to about 1 m distance.

Introduction

Biomass in the form of coarse woody residues remaining after timber harvest in pine plantations of the southeastern USA is a significant potential source of biomass for bioenergy. The Southeast and South-Central United States are estimated to contribute a total of 32 million Mg out of a total 57 million Mg of dry residue produced at the national level (Milbrandt, 2005). Removal of these woody residues has the potential to negatively affect soil quality and therefore soil productivity (Scott and Dean, 2006; Eisenbies et al., 2009). Given the potential for increased harvests of forest residues for energy production in the US Southeast, it is important to understand the effects that residue biomass harvests may have on soil quality and site productivity.

Some states have proposed guidelines for retention of woody residuals (Abbas et al., 2011). These guidelines focus on dead woody material left on site after harvesting. For example, Michigan's guidelines recommend leaving one-sixth to one-third of the woody material <4 inches (10cm) diameter on site. Wisconsin guidelines recommend leaving all the pre-harvest dead woody material and tops and limbs from10 % of the trees on site (at least 5 tons of fine woody material per acre) and leaving extra in the forest areas which lack dead woody material (Evans et al., 2010). Leaving 15-30 % of the harvestable biomass is suggested in Pennsylvania's guidelines while Missouri guidelines suggest retaining 33 % of the harvest residue. Most of these states except Michigan and Missouri suggest leaving all snags (standing dead/dying trees) possible at the harvest site (Evans et al., 2010).

The focus on post-harvest residue retention incorporated into these guidelines overlooks the role of site preparation in intensive pine plantation management in the southern United States. In the South, site preparation prior to replanting the forest often includes mechanical slash management. In many harvesting operations, woody biomass residue is pushed into windrows or piles with a bulldozer-mounted blade or rake to provide access for subsequent soil tillage operations such as bedding. Windrows are long (10-40 m) linear structures that can be 1-5 m high. Piles (sometimes referred to as spot piling) may be 5-20 m in diameter and 2-10 m high. Both of these operations radically alter the distribution of slash and may limit the assumed benefits of slash retention guidelines.

Tew and Morris (1986) studied the effect of harvesting operations (stem only vs. complete tree) and site preparation treatments (chop/broadcast burn vs. shear-pile/disk) in the North Carolina Piedmont on soil nutrients. N, P and K removal from areas near to windrows in stem-only harvest plots was 654, 40.9, and 118.4 kg/ha, respectively. In complete tree harvest, removals were less because there was not much residue left after complete tree harvesting so limited need for piling or raking. Overall, windrowing had the largest effect on nutrient displacement when compared to other treatments and harvest removals. Blumfield et al. (2006) conducted a 3-yr study in pine plantations of subtropical Australia to determine the effect of residue decomposition on nutrient availability in the top 10 cm of soils between and beneath windrows of different ages. Soil samples were analyzed for total C, total N, ^{13}C, ^{15}N, and mineralizable N. At Year 1, they found that total C and N was not significantly different at windrows and points near to windrows but at Year 3, points beneath windrows and near windrows had significantly higher values. Percent mineralizable N (PCMN) was 1-2% higher at Year 3 at and near windrow points but there was not any significant difference in Year 1 and 2 (Blumfield et al., 2006). Also, ^{13}C was significantly lower at near windrow positions as compared to points away from windrows indicating movement of labile C into the soils beneath windrows at year 3 (total %C was also higher at Year 3). It was concluded that increased levels of PCMN beneath windrows at Year 3 indicated that decomposing debris had long lasting beneficial effects on N reserves but the effects were localized at or near windrows (Blumfield et al., 2006).

Patterson et al. (2002) studied soil profile characteristics of windrowed loblolly pine plantation and found surface and sub-surface bulk density values were higher for near to windrow areas (1.53±0.02 and 1.67±0.03, respectively) as compared to areas far from windrows (1.18±0.04 and 1.51±0.04, respectively). There was not, however, any significant difference in %organic matter or K concentration at areas near to windrow and far from windrow. Site index was similar for both near to windrow (i.e., 97 ft) and far from windrow areas (i.e., 97.2 ft) (Patterson et al., 2002). In contrast to Patterson et al (2002), an earlier study by Fox et al. (1989) found site index of 31-year-old loblolly pine stand decreased by 10.5 ft following windrowing. Patterson et al. (2002) hypothesized that compaction due to windrowing may have benefitted the young pine productivity by removing woody competition.

The "windrow effect" describes the greater growth observed for near windrow trees (Fox et al. 1989). Morris et al. (1983) sampled windrows created during site preparation of a flatwoods forest in north Florida and found that greater quantities of nutrients were displaced into windrows than were removed during harvest of the site. Working on this same site, Swindel et al. (1986) later found that early growth of slash pine adjacent to these windrows was greater than slash pine at beds far from windrows and they attributed this growth difference to the improved nutrient availability near windrows and reduced availability away from windrows where organic debris and soil had been displaced. In a North Carolina study, Fox et al. (1989) showed that the influence of windrows can persist for an entire rotation. These investigators found that potentially mineralizable N and extractable K, Ca and Mg concentrations were all greater in surface soils adjacent to windrows than in the inter-windrow area of the same site 31 yrs following site preparation. Generally, soil nutrient concentrations adjacent to windrows were as great as or greater than in non-windrowed areas in adjacent stands.

The total amount of residue retention and the redistribution of these residues during windrowing or piling may both directly and indirectly influence ecosystem processes and productivity, and may interact with each other. For example, in comparison of bole-only and total tree harvest, soil temperature of micro-sites in the shade of stumps was significantly different as compared to other micro-sites and differed depending on the harvest removal. Total annual soil degree-day accumulation was 25-37% greater in the total tree harvest with vegetation control treatment than in the bole-only harvest with vegetation control treatment (Devine and Harrington, 2007). Another study conducted by Roberts et al. (2005) found that residue retention resulted in competing vegetation control and higher soil moisture as compare to treatments where residues were removed. Finally, a study by O'Connell et al. (2004) found that soil moisture was higher and soil temperature was lower at sites where residue was retained.

Given the previous research, the specific objective of this study was to investigate the effect of windrow/pile sizes created following harvest and residue removal on surrounding soil properties. To quantify these responses, measurements of nutrient availability, soil moisture, soil temperature, and CO_2 efflux were made relative to windrow/pile sizes and the distance from a pile or windrow. It is hypothesized that soil quality indicators like moisture and temperature will be more stable (lower annual variance) near the base of piles as compared to some distance away from piles because of the shadowing effect of piles/windrows and this response should be greater for larger windrow/piles. These more stable conditions should be more favorable for microbial decomposition of organic matter thus there should also be higher nutrient availability near the pile/windrow. It is further hypothesized that post-harvest residue pile/windrow size would have a significant effect on measured parameters of soil quality and these effects would be large relative to other site or treatment effects.

Materials and Methods

Study area and experimental design

The sites were located in Beaufort County, North Carolina (35° 35’ N 76° 56’ W), Glynn County, Georgia (32° 19’ N 81° 11’ W), and Effingham County, Georgia (32° 19' N 81° 10’ W). There were four replicate blocks in a randomized complete block design in each state with three GA blocks in Effingham (Brunswick, Ga) and one in Glynn county (Rincon, Ga). Each replicate block of approximately 48 ha was divided into six different treatment plots based on the amount of residual harvestable biomass retention and distribution of the residue. The six different treatments were:

- 100 RET: Tree stem wood harvest with no residual biomass harvest.
- 30RETCLUS: 30% of operationally harvestable biomass residue retained in a clustered distribution;
- 30RETDISP: 30% of operationally harvestable biomass residue retained in a dispersed distribution;
- 15RETCLUS: 15% of operationally harvestable biomass residue retained in a clustered distribution;
- 15RETDISP: 15% of operationally harvestable biomass residue retained in a dispersed pattern,

- '0' RET: Removal of all operationally (economically) harvestable biomass residues (No Biomass Harvesting Guidelines);

The climate of Beaufort County, NC is mild with a mean annual temperature of 21.8°C and average growing season rainfall of 829 mm (NOAA, 2013). The climates of both Glynn County and Effingham County are humid sub-tropical with annual temperature of 24.5°C, and average growing season rainfall of 835 mm (NOAA, 2013). The predominant soil series for the Beaufort County sites include Bayboro loam, Leaf silt loam, and Pantego loam, which are derived from unconsolidated sands and clays of sedimentary origin (NRCS, 2013). Bayboro loam (thermic Umbric Paleaqualt) is characterized by a loam surface horizon (umbric epipedon) and clay loam or clay subsurface (argillic). Pantego loam (thermic Umbric Paleaqualts) has a loam surface horizon (umbric epipedon) and a sandy clay loam subsurface (argillic). Leaf silt loam (thermic Typic Albaquults) has a silt loam surface horizon (ochric epipedon) and silty clay or clay subsurface (argillic) horizon. These soils are poorly drained to very poorly drained Ultisols, therefore require site preparation with bedding.

The predominant soil series at Glynn and Effingham County sites are Bladen fine sandy loam, Meggett fine sandy loam, Rains fine sandy loam, and Sapelo fine sands (NRCS, 2013), which are somewhat poorly drained to poorly drained Ultisols, Alfisols, and Spodosols. The Bladen fine sandy loam (thermic Typic Albaquult) is characterized by a fine sandy loam surface (ochric epipedon) horizon and clay subsurface (argillic) horizon. Meggett fine sandy loam (thermic Typic Albaqualf) features a fine sandy loam surface (ochric epipedon) horizon and clay or sandy clay subsurface (argillic) horizon. Rains fine sandy loam (thermic Typic Paleaquult) have a sandy loam surface (ochric epipedon) horizon and sandy clay loam subsurface (argillic) horizon. The Sapelo fine sand (thermic Ultic Alaquod) is characterized by a fine sand surface (ochric epipedon) horizon, fine sand spodic horizon, and a sandy clay loam (argillic) horizon. These soils require site preparation with bedding.

Study sites in Georgia are currently managed by Plum Creek Timber Company, Inc. for pulpwood and chip ‘n’ saw. Two sites were harvested at the age of 26 while the third site was harvested at age 33. Three of the four replicates received a banded herbicide treatment followed by mechanical site preparations including shearing and piling and planting was done at 1.8*3.7 m spacing (1495 trees/ha). One replicate received broadcast herbicide treatment and planting was done at 1.5*3.7 m spacing (1,794 trees/ha). Study sites in North Carolina were previously planted in loblolly pine (*Pinus taeda L.*) managed for sawtimber production and were harvested at the age of 32 to 39 years in the winter of 2010-11. Mechanical site preparation was done in all four experimental blocks which included shearing with a v-blade and woody residue was retained in the form of piles or clusters. Sites were bedded, and then hand planting was done during the winter of 2011-12. Stands had two commercial thinning entries before the final harvest and one broadcast herbicide treatment of 10 gallons per acre solution of 48 oz acre of Chopper© + 12.8 oz. acre of Red River Supreme surfactant for herbaceous weed control.

To study the effects of residue retention in the form of piles or windrows, 10 piles from the North Carolina sites and 10 windrows from the Georgia sites were randomly selected from across all blocks. These piles and windrows were visually classified in to small, medium, and large size depending upon their height, width and length. Each pile and windrow was systematically located with a field portable Garmin eTrex Summit HC GPS receiver (Garmin International, Inc., Olathe, KS) and location was marked with a painted pole.

For data collection, 10-13 m long transects running perpendicular to the pile/windrow and to the associated beds and inter-beds were established starting from the base of the pile/windrow. For sampling purposes, each transect was marked with fluorescent flags at nine points. The first three points were at 0 m (P1), 0.5 m (P2), and 1 m (P3) from the base of the pile/windrow and the other six points at 3 beds (B1, B2,B3) and 3 inter-beds (IB1, IB2, IB3) consecutively along the transect (Fig. 3.1).

Pile/Windrow Field Sampling

In August 2012, mineral soil samples were collected from 0-15 cm depth using an Oakfield probe (2 cm inside diameter) at both North Carolina and Georgia sites. The samples were collected at each of the nine points along the transects. Six to eight individual cores were removed at each point and composited in a standard Cooperative Extension soil sample bag. Samples were returned to the Forest Soils Lab in Athens, GA for later analysis.

To study the potential effects of pile/windrow on surrounding soil nutrients, ion-exchange resin capsules from UNIBEST (UNIBEST International, Walla Walla, WA) were installed at five points on the transect starting from the base of the windrow (points 1 to 5) at 7 cm depth in July 2012 (Fig. 3.1). Resins were prepared in the laboratory by soaking in 1M HCl and shaking for 8 hours. The HCl solution was then replaced with de-ionized (DI) water and resin capsules were shaken for another 8 hours. Finally, the centrifuge tubes were filled with fresh DI water until field installation. Every two to three months, previously installed resin capsules were recovered from the soils, rinsed with DI water and placed in 50 ml centrifuge tubes filled with DI water. A new set of resin capsules were installed at the same locations for the next period of two to three months. The process was continued until summer of 2013 for a total of five collections.

Effects of windrows on soil moisture were also investigated at Georgia. Volumetric Water Content (VWC%) data were collected using Time Domain Reflectometer (TDR 100) Soil

Moisture Meter with 20 cm long probes (Spectrum Technologies Inc., Plainfield, IL). VWC data was collected at 0-20 cm depth at points 1 to 9 along each transect (Fig. 3.1). On each field visit, VWC data was collected thrice at each point and averaged. VWC data were collected every two to three months throughout a year (July 2012 to July 2013).

To study the effects of windrows in Georgiaon soil temperature, measurements were taken at multiple distances from the base of windrows with temperature data loggers (Thermochron ibuttons, Embedded Data Systems Inc. Model: Thermochron ibutton DS1921-G, Lawrenceburg, KY) installed near to the ion exchange resin capsules at five points (1-5) along the transect (Fig. 3.1). Like ion resin capsules, temperature ibuttons remained installed in the field for 2-3 months until the next field visit. Temperature ibuttons were programmed to collect temperature data every 4 hours. During each field trip, data from ibuttons was downloaded to a laptop and ibuttons were re-programmed and re-installed to collect data for the next period. Temperature data was collected for a period of one year (July 2012 to August 2013).

Similarly, CO_2 efflux data was collected in Georgiaat points 1 to 9 along the transects for studying the effect of windrows on soil respiration. CO_2 efflux (μmol CO_2 m^{-2} s^{-1}) was measured using an Infra-Red Gas Analyzer (IRGA) - Li 6400-09 with a soil chamber (LI-COR Environmental, Lincoln, NE). CO_2 efflux data was collected multiple times over a period of 1 year from July, 2012 to July 2013 at intervals of 2-3 months.

Sample Preparation and Analysis

Mineral soil samples were air-dried, sieved through a 2mm screen and a 2 g sample was further ground using a SPEX 8000 ball mill grinder (Spex Sample Prep, LLC, Metuchen, NJ). For total carbon and nitrogen concentration analysis, ~0.100 g of ground soil was weighed into a tin capsule and combusted in a CHN Elemental Analyzer (CE Instruments – model NC2100, CE Elantech Inc., Lakewood, NJ).

Air-dried and sieved mineral soil samples were analyzed for exchangeable Ca, Mg, K and P. For analysis, 10 g of soil and 50 ml Mehlich I extract (0.05N HCl and 0.025N H_2SO_4 mixture) were mixed in a 125 ml Erlenmeyer flask (Mehlich, 1953). The soil mixture was shaken for 5 minutes on a mechanical shaker followed by filtration with Whatman no. 42 filter paper. The extract was stored in small plastic bottles at $4^{O}C$ until analysis by Inductively Coupled Plasma-Mass Spectrometry (Elan 6000, Perkin-Elmer).

Ion exchange resin capsules were brought back to the laboratory and further rinsed with DI water to remove adhering soil material. Resin capsules were placed in a new set of 50 ml centrifuge tubes filled with DI water and shaken for 4 hours. This step was repeated with fresh DI water until the solution remained clear after shaking. This final DI water rinse was followed by 50 ml of 1M HCl for ion exchange purposes, shaken for 8-10 hours, and extracts were stored at $4^{O}C$ for future analysis of Ca, Mg, K, and P on ICP-MS.

Statistical Analysis

The total soil organic carbon (SOC), total nitrogen, soil exchangeable and resin extractable Ca, Mg, K, and PO_4-P, volumetric water content (%), soil temperature (°C), and CO_2 efflux (μmol CO_2 m^{-2} s^{-1}) data were analyzed for windrow/pile size and distance from the windrow/pile as a two-way ANOVA using the SAS Proc MIXED procedure (Statistical Analysis Systems software, version 9.3; SAS Institute Inc. 2010, Cary, NC). Tukey's means separation procedure was used if significant differences (α=0.05) of main effects were found during analysis of the data.

Results

Residual material in Georgia was retained in the form of windrows that, on average, were much larger in size than the piles in North Carolina. The largest piles in North Carolina were comparable in size to the smaller windrows in Georgia. Therefore, data from both sites were analyzed separately.

Georgia Mineral Soil

There was no significant effect of windrow size on total soil N ($F_{2, 7}$=3.54, p=0.0866) or total soil C ($F_{2, 7}$=1.32, p=0.3273) concentrations. Distance from pile also did not have any significant effect on total soil N ($F_{8, 56}$=0.65, p=0.7300) or total soil C ($F_{8, 56}$=0.49, p=0.8553). Mean total soil C did, however, follow a decreasing trend from point P1 to P3. Mean total soil C was higher on beds (i.e., 3.3±0.3 µg g^{-1}) as compared to inter-beds (IB1, IB2, and IB3) (i.e., 2.9±0.2 µg g^{-1}) (Table 3.3). Similarly, mean total soil N was higher on beds (0.82±0.06 µg g^{-1}) as compared to inter-beds (0.54±0.02 µg g^{-1}).

Neither windrow size nor distance from the windrow significantly affected PO_4-P concentration at these sites (Table 3.1). However, P concentration was greater near the windrow and decreased with increasing distance from the windrow (Table 3.3.) but after 1 m the effect was overshadowed by the effects of beds and inter-beds. When averaged across windrow size, PO_4-P concentration was greater in the beds (12.6±1.9 µg g^{-1}) than in the inter-beds (9.1±1.2 µg g^{-1}).

There was no significant effect of windrow size or distance from windrow on Ca concentration in surrounding soil (Table 3.1). When averaged across beds and inter-beds, Ca concentration was found to be greater adjacent to medium sized windrows (i.e., 743±43.8 µg g^{-1})

than adjacent to large (i.e., 265±29.1 µg g^{-1}) or small windrows (i.e., 400±22.4 µg g^{-1}). On average, beds had higher Ca concentrations (i.e., 485±67 µg g^{-1}) as compared to inter-beds (409±62 µg g^{-1}). Although differences were not significant, mean Ca concentration was greater near the base of large windrows and declined from P1 to P3. This relationship was not observed for medium or small windrows (Table 3.4).

Similarly, Mg concentrations did not vary significantly with distance from the windrow (Table 3.1). A pattern similar to Ca was observed for mean Mg concentration, which was greater adjacent to medium-sized windrows (95µg g^{-1}) than adjacent to large (43 µg g^{-1}) or small size windrows (65 µg g^{-1}). On average, beds also had higher Mg concentration (67±7 µg g^{-1}) than inter-beds (60±9 µg g^{-1}).

Windrow size did not have any significant effect on K concentration ($F_{2, 7}$=0.12, p=0.8902) but K concentration did vary significantly along the transects ($F_{8, 56}$=2.61, p=0.0170). When averaged across windrow size, K concentration followed a declining pattern from P1 to P3 with P1 having the greatest concentration (55±11.2 µg g^{-1}) followed by P2 (35±5 µg g^{-1}) and P3 (32±4.3 µg g^{-1}). Beds had higher average K concentration (38±3 µg g^{-1}) than the inter-beds (27±2 µg g^{-1}) (Table 3.4).

Ion-Exchange Resin Capsules - Georgia

Resin Ca concentration varied significantly over time from July 2012 to July 2013 ($F_{4,140}$=4.40, p=0.0022) but neither windrow size ($F_{2,7}$=1.79, p=0.2359) nor distance from the base of windrow ($F_{4,28}$=1.32, p=0.2852) had a significant effect (Table 3.2). When averaged across windrow size and time of sampling, there was no consistent pattern in mean Ca concentration when moving from P1 (base of windrow) to the first inter-bed (Fig. 3.2).

Resin Mg varied significantly along the transects with distance from the windrow and with time of sampling but windrow size did not have a significant effect (Table 3.2). Resin Mg followed a declining pattern when moving away from the base of the windrow (P1>P2>P3>IB) with approximately a 10 mg l^{-1} difference between mean concentration at P1 and IB (Fig. 3.2) when averaged across windrow size and time of sampling.

Resin K varied significantly with windrow size, distance from the pile, and time of sampling (Table 3.2). When averaged across time of sampling, mean K concentration ranged between 50 to 235 mg l^{-1} at large sized windrows whereas in medium sized windrows resin K ranged from 25 to 155 mg l^{-1}. In small windrows, the range was even smaller, i.e. 50 to 135 mg l^{-1} (Fig. 3.3). Overall, resin K followed a declining pattern when moving away from the base of the windrow to the bed and inter-bed (Fig. 3.2).

Like Ca, PO_4-P did not vary significantly along the transects nor with windrow size. Time of sampling, however, had a significant effect on resin PO_4-P concentrations at the Georgia sites (Table 3.2). Although there was no significant distance effect, resin PO_4-P concentration declined with distance from the base of windrows but the pattern was limited to a 1 m distance (Fig.3.2).

There was significant variation in soil temperature depending upon time of collection ($F_{12, 368}$=1766.4, p<0.0001) and distance along the transect ($F_{8, 56}$=8.88, p=0.0001). However windrow size did not affect temperature significantly ($F_{2, 7}$=0.38, p=0.6491). Mean temperature varied over the period of 13 months along the transect (Fig. 3.4). Mean soil temperature for all the 10 windrows during winter months (November 2012 to March 2013) was observed to be 5-15^{O}C lower than the summer months (July 2012 to October 2012, April 2013 to July 2013) (Fig. 3.4). Generally, soil temperatures fluctuated less in soils immediately adjacent to windrows.

During winter months, P1 (base of windrow, 0 m) had higher mean soil temperatures than B1 (bed) and IB1 (inter-bed). In summer months, P1 was cooler as compared to bed and inter-bed.

As would be expected, volumetric water content (VWC %) varied by time of collection ($F_{5, 312}$=71.84, p<0.0001). It was also affected by distance from the windrow ($F_{8, 56}$=5.44, p<0.0001). Windrow size did not result in any significant changes in soil moisture ($F_{2, 7}$=0.72, p=0.5186). Soil moisture was found to be lowest in July 2012 and July 2013 and highest in August 2013 (Fig. 3.4). Point 3 (1 m from the base of windrow) had the highest mean soil moisture throughout the period of 13 months of data collection.

CO_2 efflux (soil respiration) varied significantly with time of collection over a period of one year ($F_{5, 221}$=52.63, p<0.0001). Windrow size ($F_{2, 7}$=1.01, p=0.4129) or distance from the windrow ($F_{8, 56}$=1.64, p=0.1351) did not affect the soil respiration significantly. There was a generally decreasing pattern in mean soil respiration from P1 to P3 when averaged across windrows and time (Fig. 3.5). Mean soil respiration was found to be lowest in beds (average of B1, B2, B3) as compared to inter-bed (average of IB1,IB2,IB3) as well as being lower than respiration at the first three points (P1 to P3) along the transect.

North Carolina Mineral Soil

There was no significant effect of pile size or distance on total C and N concentration. Mean total soil C was highest near to the base of the piles (P1) and decreased with increasing distance from the pile (P1>P2>P3). Mean total soil C was higher at inter-beds (i.e., 6.9±0.4 µg g^{-1}) when compared to beds (i.e., 4.6±0.2 µg g^{-1}). Similarly, mean total N was higher at point P1, then declined at P2 and P3 (Table 3.5). Total N followed the same pattern as soil C, with higher concentrations in inter-beds (i.e., 0.23±0.02 μg g^{-1}) compared to bed locations (i.e., 0.15±0.01 μg g^{-1}) (Table 3.5).

Neither pile size nor distance from the pile significantly affected extractable P concentration at these sites (Table 3.1). P concentration did have a trend of higher values near to the base of piles and decreased with increasing distance from the pile (Table 3.5) but after 1 m distance the effect was overshadowed by bed and inter-bed differences. When averaged across pile size, PO_4-P concentration was higher in the beds (19.3±3.4 μg g^{-1}) compared to inter-beds (17.1±2.2 μg g^{-1}).

Pile size or distance from the pile did not affect the extractable Ca concentration at North Carolina sites (Table 3.1). When averaged across distance, medium piles had the highest mean Ca concentration (108±13.1 μg g^{-1}) as compared to large (97±11 μg g^{-1}) and small (57±7 μg g^{-1}) piles. When averaged across pile size, Ca concentration was higher at inter-beds (92±13.4 μg g^{-1}) as compared to beds (64±11.7 μg g^{-1}) (Table 3.6).

Extractable Mg concentration was not affected by either pile size or distance from the pile (Table 3.1). Medium piles had the highest mean Mg concentration (28±3.2 μg g^{-1}) as compared to large (24±3 μg g^{-1}) and small (17±1.7 μg g^{-1}) piles (Table 3.5). Mg concentration was higher on inter-beds (25±3.5 μg g^{-1}) as compared to beds (17±2 μg g^{-1}) when averaged across the pile sizes (Table 3.6).

Like Ca and Mg, pile size or distance from the pile did not affect the extractable K concentration at these sites (Table 3.1). When averaged across distance, medium piles had the highest mean K concentration (52±3.8 μg g^{-1}) as compared to large (42±4.7 μg g^{-1}) and small (32±2.1 μg g^{-1}) piles (Table 3.6). When averaged across pile size, K concentration was higher at inter-beds (41±3.8 μg g^{-1}) as compared to beds (35±3.2 μg g^{-1}) (Table 3.6).

North Carolina Ion Exchange Resin Capsule

Resin recoverable Ca, Mg, K, and P significantly varied over time from July 2012 to July 2013 whereas pile size did not have a significant effect on any of these macro-nutrients (Table 3.2). There was significant variation in resin K with distance from the base of piles (F=5.77, p=0.0016) but distance was non-significant for resin Ca, Mg, or P (Table 3.2). When averaged across pile size and time of sampling, resin K followed a declining pattern when moving from P1 (base of pile) to inter-bed and bed (Fig. 3.6). Unlike K, Ca, Mg, and P did not follow any consistent pattern with distance from pile (Fig.3.6).

Discussion

There are concerns over potential woody residue harvesting for renewable energy in Southeastern pine plantations as removal of nutrient rich branches and needles can constitute a substantial loss from forest soils. Various studies have compared intensive harvesting techniques like whole tree harvesting to conventional harvesting and have observed losses in conifer growth, soil acidification, and water and soil nutrient depletion (Proe et al., 1996; Egnell and Leijon, 1997; Staaf and Olsson, 1991; Olsson et al., 1996; Thiffault et al., 2006, 2011; Wall, 2008; Walmsley et al., 2009; Saarsalmi et al., 2010). Due to increasing removal of residual woody biomass for bio-energy and bio-fuel production some states have proposed guidelines for retention of woody residuals (Abbas et al., 2011). The current study focuses on the effect of different levels of woody biomass retention and the resulting windrows and piles of variable size and dispersion on soil quality. This study is somewhat unique in investigating different levels of residual woody biomass retention and assists in validating proposed guidelines.

In the current study, there was no effect of windrow size on total C and N, extractable Ca, Mg, or P but K was significantly affected. Distance from the base of windrows and time of sampling had a significant effect on Ca, Mg, and K. A trend of higher concentrations at the base of windrows/piles was observed, although was not always significant. Brandtburg and Olsson (2012) found that intensity of harvest residue removal (i.e., whole tree harvesting, branch and stem harvesting, conventional harvesting) did not have any significant effect on exchangeable Ca, Mg and K at 0-20 cm depth. A study by Wilhelm et al. (2013) in northwest Wisconsin included different levels of harvesting intensity treatments (i.e., un-harvested, whole tree harvest, biomass removed except <5 cm tops and branches, and biomass removed except <10 cm tops and branches). Ion-exchange resin were installed and mineral soil samples were also collected at surface (0-8cm) and sub-surface (8-60cm) and analyzed for N, P, K ,Mg, Ca. Harvesting intensity did not have any significant effect on N, Ca, Mg, and K after two years of harvest (Wilhelm et al., 2013).

Surface organic matter, such as windrows/piles, can act as a mulching and shading agent and a few studies have found that shading micro-sites can help in improved survival and growth of seedlings that can otherwise die in high temperature conditions (Minore, 1986; Flint and Childs, 1987). Soil temperature in general is related to seedling survival and germination, and growth (Minore, 1986; Carlson and Miller, 1990; Flint and Childs, 1987). Results from this study in GA, showed that windrow size itself did not have any significant effect on soil temperature but soil temperature was significantly affected by distance from the windrow. Windrows had a shadowing effect as there was lower variability in soil temperature near to the windrow base. In other words, temperatures near to the base of windrows were warmer in winters and cooler in summers as compared to locations that were at a distance from the windrow.

Like temperature, soil moisture can also impact seedling growth. Many studies have looked at the effect of soil moisture on plant growth and amply demonstrated that high soil moisture tension can lead to leaf water deficit and can negatively affect seedlings by reducing seedling growth and decreasing height elongation (Rutter and Sands, 1958; Sands and Rutter, 1959; Stransky and Wilson, 1964). Removal of residual biomass can result in both increased surface soil temperature and reduced soil moisture thus impacting seedling growth (Roberts et al, 2005). In this study, results indicated that soil moisture was significantly affected by distance from the windrow but the pattern was not uniform with distance. Overall, medium windrows had higher soil moisture as compared to small and large windrows, but there was no clear basis for this observation. Soil moisture was lowest in the bed areas; a logical result since bedding is designed to achieve better aerated soil conditions for the survival of pine seedlings in these poorly drained Coastal Plain sites. On the contrary, throughout the study, it was found that soil moisture was highest at 1 m from the base of windrows followed by locations at the base (<1m) and then inter-bed areas. Higher moisture in inter-beds and at the base of windrows might be explained by lower soil disturbance in the inter-bed areas and the fact that windrows are created on the inter-bed areas. The mechanisms resulting in increased moisture content 1 m from the windrows are uncertain but there was some vegetation growth such as grasses in the inter-bed areas and at the base (0-50cm) of windrows, which may reduce soil moisture explaining higher soil moisture levels at 1 m distance from the base where vegetation was generally sparser. Another factor might be higher compaction levels at the transition from windrows to the first bed due to machinery use for site preparation. In this study, bulk density increased from 1.21 g cm^{-3} to 1.41 g cm^{-3} following harvest and site preparation. Patterson et al. (2002) found that areas away from windrows had higher bulk density as compared to surfaces beneath the windrows.

These higher bulk densities are likely associated with reduced macropore space and drainage and thus higher field capacity moisture content.

Interactions of soil temperature and moisture in response to windrows should also be reflected in soil microbial respiration. Soil microbial respiration of CO_2 produced as a result of organic matter decomposition in soil comprises a large flux of C from forest ecosystems to the atmosphere. McDaniel et al. (2014) found that after harvests, when enough moisture is available, there is a significant increase in soil respiration. Another study, however, proposed that forest disturbances reduce microbial biomass and thus soil respiration; and found a 19.1% decrease in microbial biomass following harvests (Holden and Treseder, 2013). In the current study, like soil temperature, soil respiration was higher near large size windrows in general when compared to small and medium size windrows, however, the difference was not significant. Soil respiration and distance from the windrow were also not significantly related to each other, although in general soil respiration was higher near the windrows and in the inter-bed area. This observation might be due to the presence of organic debris, and suitable soil moisture and temperature at these locations. Results also indicate that mean soil respiration was lowest in beds. Generally, bedding incorporates organic matter and provides a tillage effect, both of which should increase respiration. Thus, the reduced respiration was unexpected. It may reflect differences in temperature, moisture and or differences in the quality of organic materials between beds and interbeds.

It is generally assumed that greater tree growth in planted rows adjacent to windrows or piles is a result of increased nutrient availability. Our results do not indicate major differences in availability during the first year following plantations establishment. However, improved moisture and reduced temperature fluctuations did occur immediately adjacent to windrows.

Perhaps early growth responses like those reported by Swindel et al. (1986) are in part due to these environmental factors as opposed to nutrient enrichment. Alternatively, rather than soil conditions being improved near windrows, increased growth may be due to tree roots extending into the windrow. Furthermore, it may be only after a number of years, as opposed to the first year measured here, that nutritional benefits of planting near windrows are significant. Fox et al. (1989) showed that the impact of windrows/piles can last throughout the remainder of the rotation so questions of woody biomass retention should continue to be evaluated.

Conclusion

Windrows and piles of residual woody biomass that remained on site in different sizes after residual retention treatments had limited effects on soil attributes. In both NC and GA retention treatments included removal of all operationally harvestale biomass residues, 15 and 30% retention of residual woody biomass, and no biomass harvesting. Also, in the 15 and 30% treatment remaining woody residue was returned to the site in a dispersed or clustered arrangement. In the latter two cases treatments were designed to consider how arranging remaining biomass might impact site attributes of wildlife habitat or soil productivity. One lesson from this research was that site preparation treatments prior to planting might have larger impacts on residue configurations than the extent of harvest retention of residuals. Also, windrow/pile sizes (i.e., small, medium, and large) had little effect, although distance from windrows/piles had some effect on temperature (lowest variance near to windrow/pile) and soil K concentrations. These documented limited impact occurred in the 1 year post-site preparation period evaluated.

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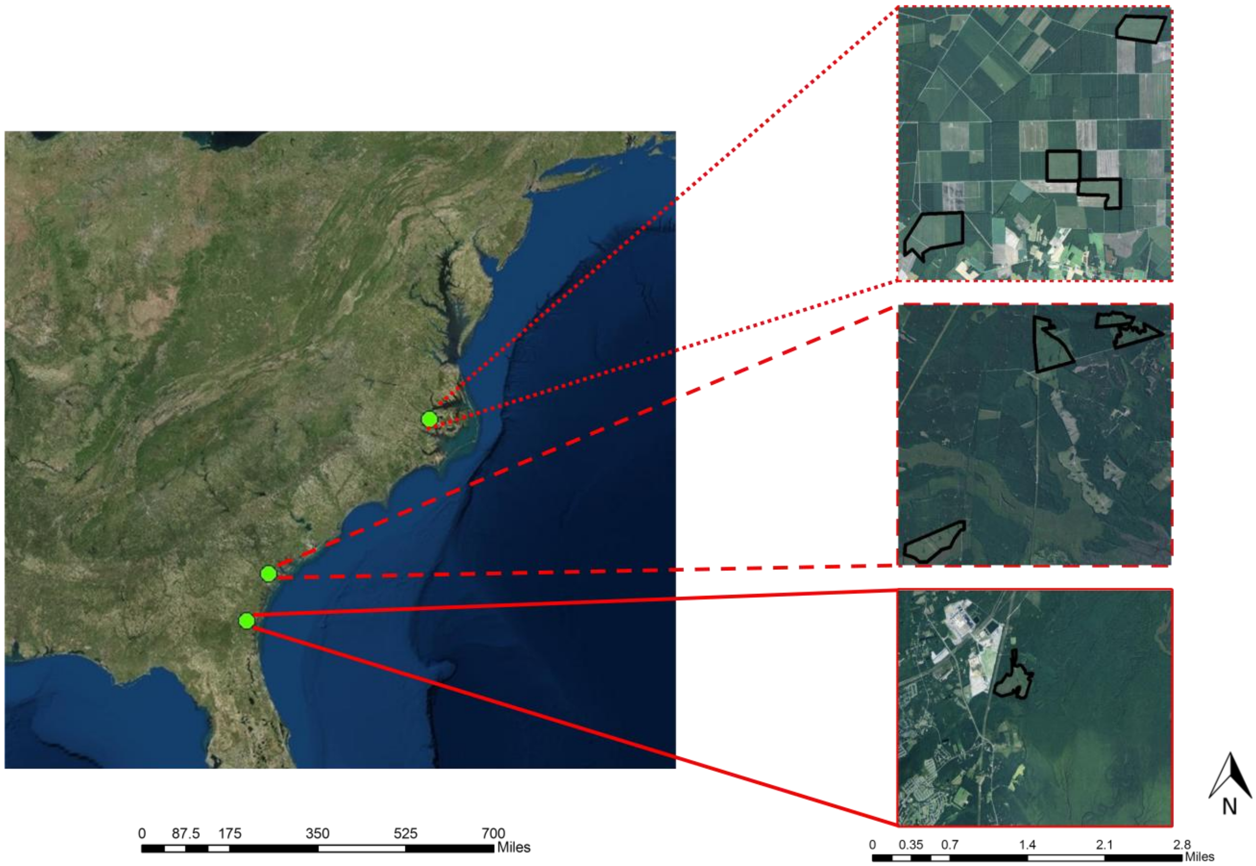

Figure 3.1. Map of the Biomass Harvesting Guideline study area showing the location of the four replicate blocks in Glynn (three replicate blocks) and Effingham County (one replicate block), Georgia, and four replicate blocks in Beaufort County, North Carolina.

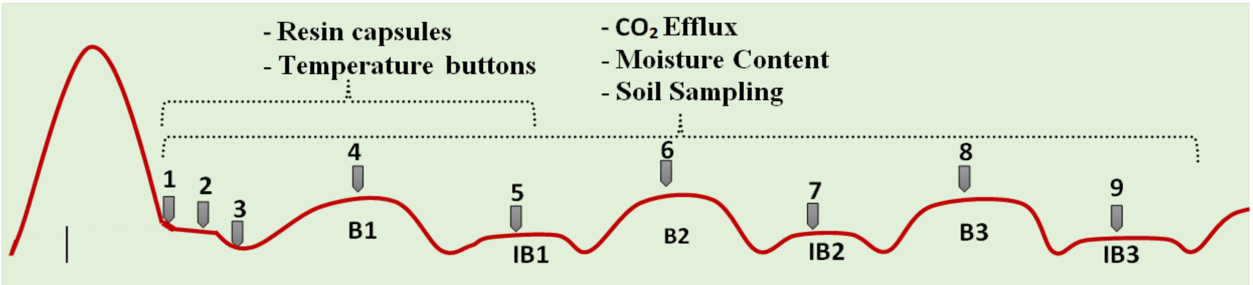

Figure 3.2. General sampling pattern along a transect extending from the base of a windrow in the left. Points 1, 2, and 3 are at 0, 0.5, and 1.0m from the windrow with point 4, 6, and 8 being replicate samples on beds (i.e., B1, B2, and B3) and points 5, 7, and 9 being inter-bed replicate samples (i.e., IB1, IB2, and IB3).

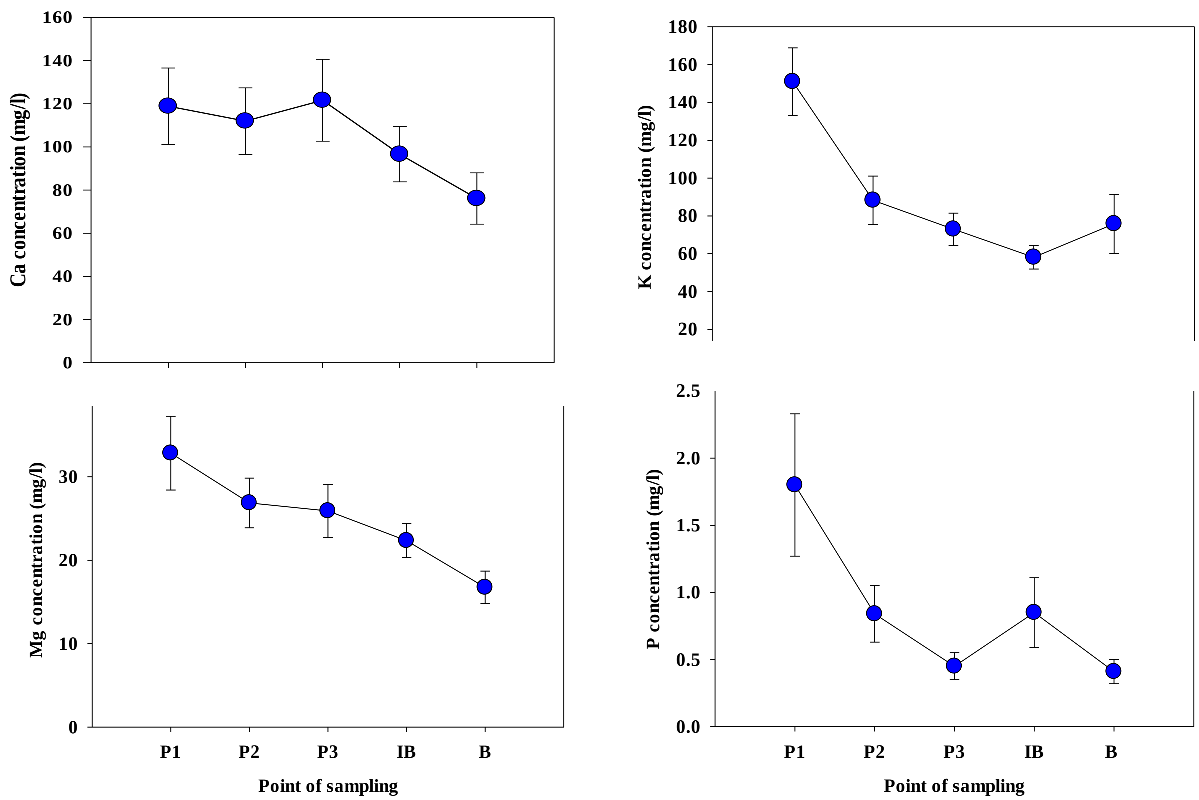

Figure 3.3. Mean extractable resin Ca, Mg, K and P concentrations (mg l^{-1}±S.E.) shown along a transect with distance from the windrows averaged across windrow sizes (large, medium and small, n= 10) and date of sampling (n=5) at Rincon and Brunswick, Georgia.

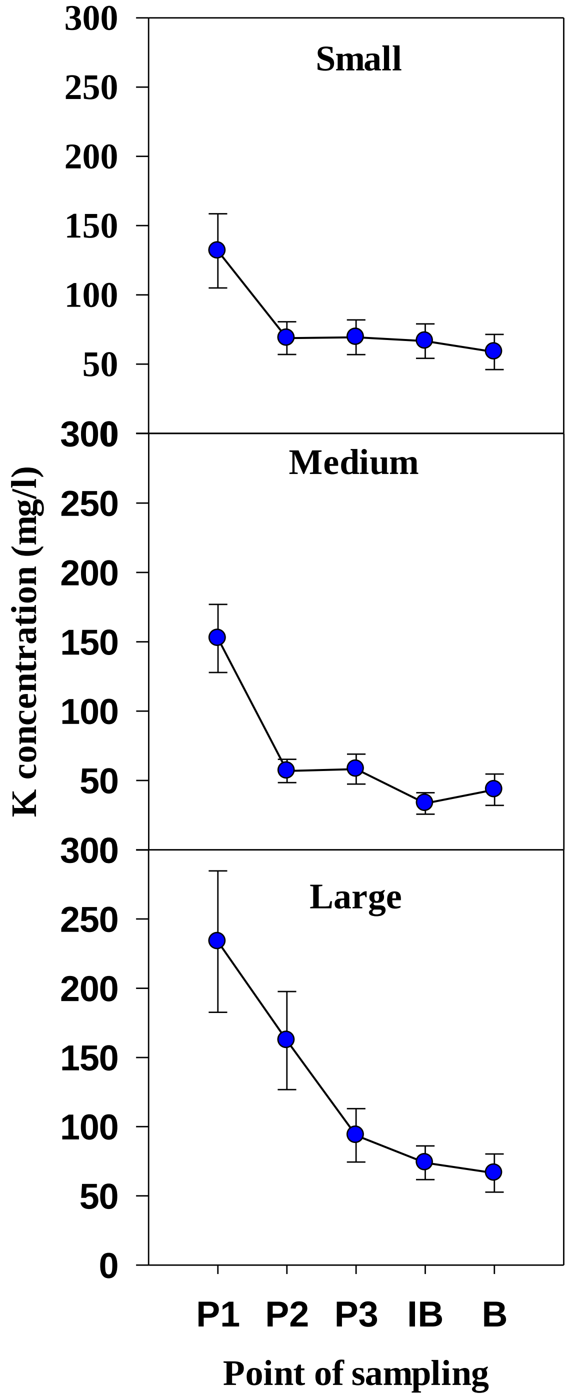

Figure 3.4. Mean extractable resin K concentration (mg l^{-1}±S.E.) in ion exchange resin capsule extracts al ong a transect at P1 (base of windrow) to B (first bed) from windrows averaged across time of sampling (July 2012 to July 2013, n=5) for large (n=3), medium (n=4) and small (n=3) windrows in pine plantations in the lower coastal plains of Georgia.

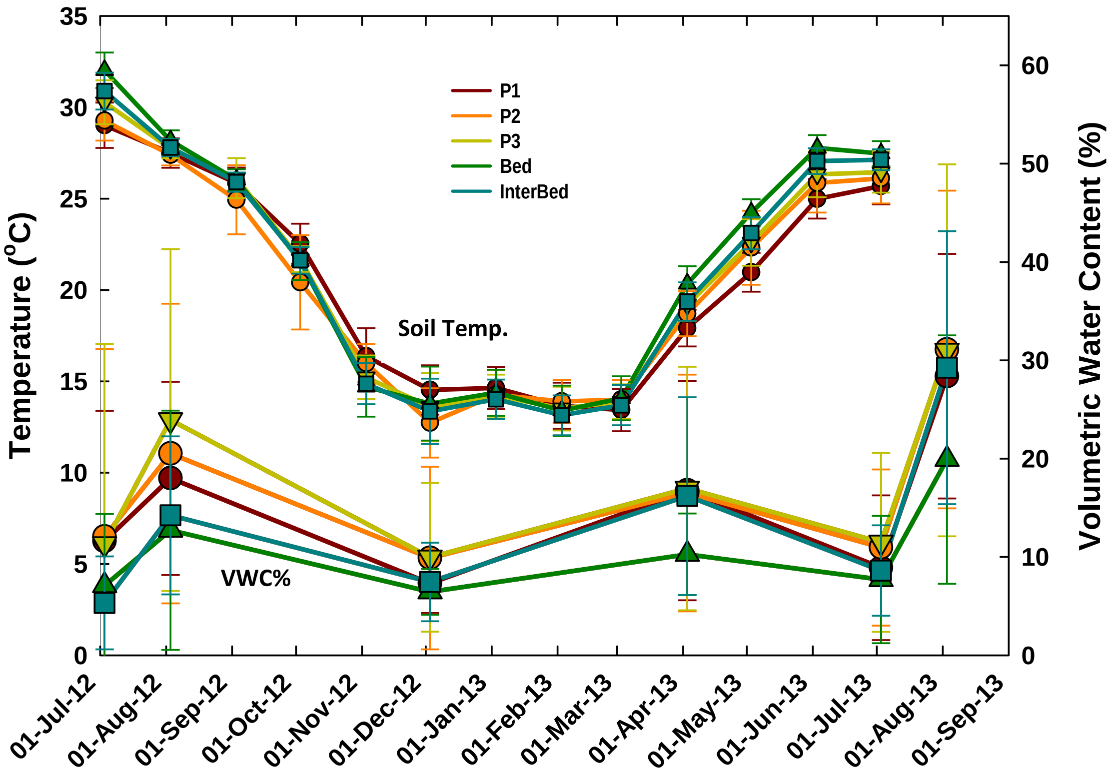

Figure 3.5. Mean (±S.E.) soil temperature data (°C) collected from July 2012 to July 2013 (n=13 dates) and mean volumetric water content (VWC %) data collected from July 2012 to August 2013 (n=6 dates) (bars represent ±S.E.) in Georgia. Data shown here are averaged across windrow size (large, medium, small, n=10).

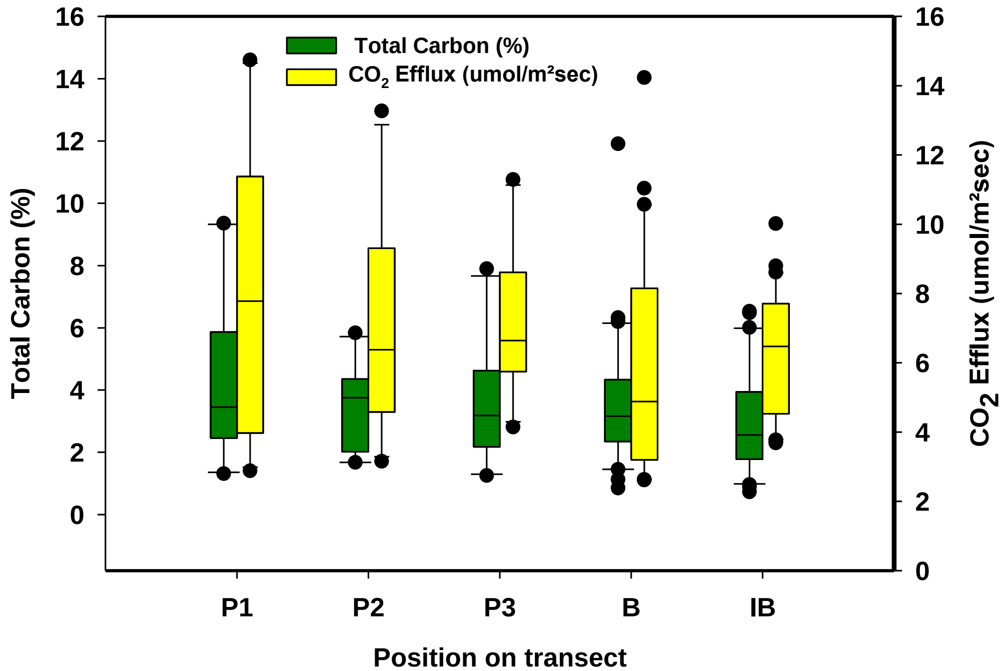

Figure 3.6. Total carbon in 0-15 cm mineral soil (%±S.E) and CO_2 efflux (µmol m^{-2} sec^{-1} ±S.E.) at P1 (base of windrow) to IB (first inter-bed) along the transect averaged across a period of 12 months (July 2012 to July 2013) and windrow size (large, medium, small, n=10) in Georgia. Boxes represent fifty percent of the data with center point line as median. Lower limit of the box is twenty five quartile (Q1) and upper limit is seventy five quartile (Q3). The lowest point of the lower whisker is Q1 – 1.5 * (Q3-Q1) and the highest point of upper whisker is Q3 + 1.5 * (Q3-Q1). The black points represent outliers.

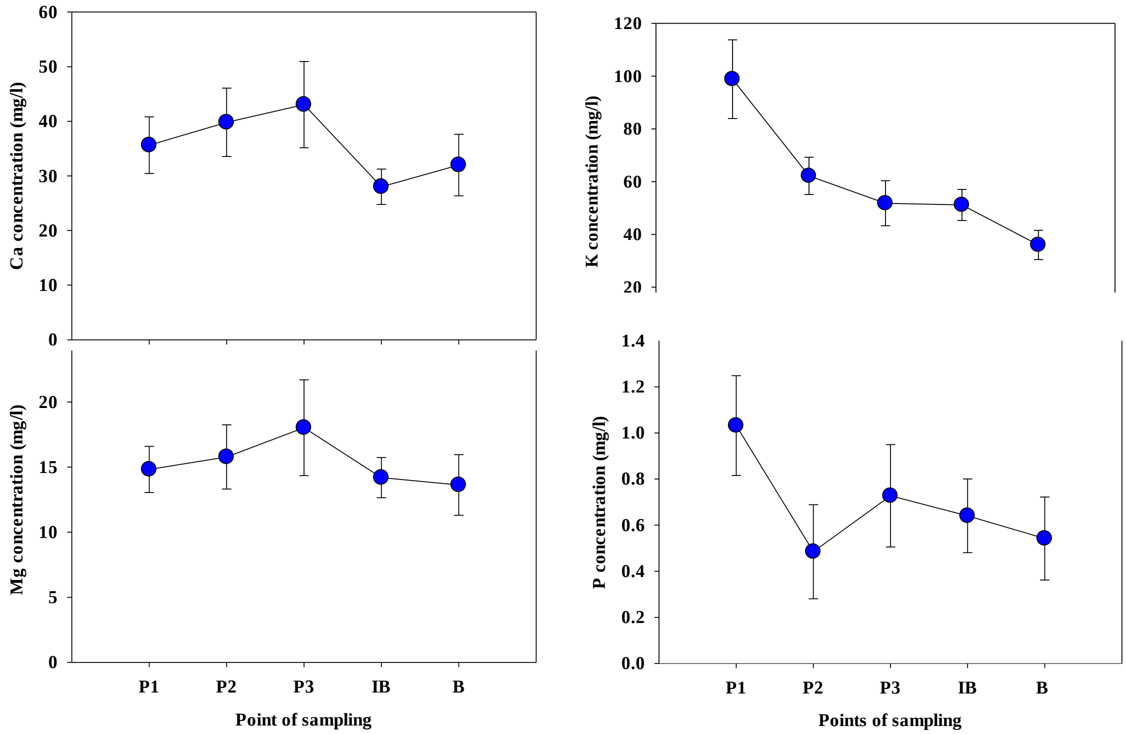

Figure 3.7. Mean (±S.E) extractable resin Ca, Mg, K and PO_4-P concentrations (mg l^{-1}) shown along the transect averaged across pile size (Large, medium and small, n= 10) and date of sampling (n=5) in North Carolina.

Table 3.1.Statistical summary (probability>F) of effect of windrow/pile size, distance from the base of windrow/pile, and the interaction on macro-nutrients analyzed from soil samples collected in August 2012 at Georgia and North Carolina study sites.

Effect	**Georgia**	**North Carolina**
	p value	
	---------------*Ca*-------------	
Windrow/pile size	0.532	0.412
Distance	0.308	0.429
Windrow/pile size*Distance	0.399	0.944
	---------------*Mg*---------------	
Windrow/pile size	0.370	0.227
Distance	0.309	0.315
Windrow/pile size*Distance	0.359	0.893
	---------------*K*---------------	
Windrow/pile size	0.890	0.263
Distance	0.017	0.174
Windrow/pile size*Distance	0.210	0.926
	---------------*P*---------------	
Windrow/pile size	0.449	0.454
Distance	0.807	0.868
Windrow/pile size*Distance	0.997	0.851

Table 3.2. Statistical summary (probability>F) of effect of windrow/pile size (n=10) (small, medium, and large), distance from the base of windrow/pile (5 distances), time of sampling (5 dates), and the interactions on macro-nutrients analyzed from ion-exchange resin extracts obtained five times during a period of one year (July 2012 to July 2013) at Georgia and North Carolina study sites.

Effect	**Georgia**	**North Carolina**
	p value	
	--------------*Ca*------------	
Windrow/pile size	0.2359	0.8145
Distance	0.2852	0.2066
Windrow/pile size*Distance	0.3716	0.3469
Time	0.0022	<.0001
Windrow/pile size*time	0.9819	0.9654
Distance*Time	0.9216	0.7649
Windrow/pile size*Distance*Time	0.9995	0.9205
	-------------*Mg*-------------	
Windrow/pile size	0.6073	0.8611
Distance	**0.0301**	0.687
Windrow/pile size*Distance	0.1224	0.7958
Time	0.0003	<.0001
Windrow/pile size*time	0.9583	0.9941
Distance*Time	0.7496	0.5925
Windrow/pile size*Distance*Time	0.9785	0.6036
	-------------*K*-------------	
Windrow/pile size	**0.0153**	0.0719
Distance	**<.0001**	0.0016
Windrow/pile size*Distance	0.0506	0.2801
Time	<.0001	0.0002
Windrow/pile size*time	0.4143	0.8268
Distance*Time	0.2386	0.481
Windrow/pile size*Distance*Time	0.8112	0.5107
	--------------*P*------------	
Windrow/pile size	0.7162	0.2102
Distance	**0.0036**	0.4888
Windrow/pile size*Distance	0.4471	0.684
Time	0.0143	0.0033
Windrow/pile size*time	0.7838	0.8697
Distance*Time	0.7513	0.8642
Windrow/pile size*Distance*Time	0.9419	0.4744

Table 3.3. Mean (±S.D.) total carbon and nitrogen, mean Mehlich I extractable P in mineral soil samples collected at 0-15 cm depth averaged across all windrow sizes (n=10) (small n=3, medium n=4, and large n=3) for sampling locations (9 distances) along the transect. Samples were collected in August 2012 at Rincon and Brunswick, Georgia.

Location	Average Distance	Mean Total Carbon	Mean Total Nitrogen	Mean Extractable P conc.
	---------- m ---------	----------------- %	-------------------	----------- μg g^{-1}----------
P1	0	4.10 (1.12)	0.12 (0.01)	13.2 (9.0)
P2	0.5	3.38 (0.32)	0.72 (0.01)	10.8 (8.0)
P3	1	3.46 (1.02)	0.79 (0.03)	10.7 (7.9)
B1	2.64	3.29 (0.82)	0.71 (0.01)	12.0 (10.3)
IB1	4.5	3.16 (0.61)	0.53 (0.01)	9.6 (7.8)
B2	5.69	3.90 (0.28)	0.86 (0.01)	12.3 (9.1)
IB2	7.9	2.71 (0.89)	0.58 (0.03)	8.7 (9.0)
B3	9.7	3.48 (2.73)	0.89 (0.07)	13.7 (15.2)
IB3	11.38	3.00 (0.79)	0.52 (0.02)	8.9 (4.8)

Table 3.4. Mean (±S.D.) Mehlich I extractable Ca, Mg, and K in mineral soil samples collected from location P1 to IB3) (9 locations) at 0-15 cm depth along the transect of small (n=3), medium (n=4), and large (n=3) windrows in August 2012 at Rincon and Brunswick, Georgia.

Windrow size	Location on Transect	Distance	Mean Extractable concentration		
			Ca	Mg	K
		--- m ---	--------------------- μg g^{-1}	----------------------	
Small	P1	0	439 (315)	69 (49)	33 (15)
	P2	0.5	388 (316)	64 (47)	29 (9)
	P3	1	496 (433)	95 (52)	27 (12)
	B1	2.63	405 (178)	69 (29)	39 (13)
	IB1	4.5	330 (235)	58 (39)	31 (9)
	B2	5.7	374 (346)	57 (32)	27 (9)
	IB2	7.9	313 (226)	39 (12)	18 (6)
	B3	9.7	502 (320)	81 (53)	55 (55)
	IB3	11.39	358 (130)	51 (4)	40 (40)
Medium	P1	0	932 (100)	121 (64)	67 (18)
	P2	0.5	766 (916)	100 (73)	45 (12)
	P3	1	906 (982)	109 (60)	41 (13)
	B1	2.63	702 (686)	82 (44)	28 (12)
	IB1	4.5	745 (758)	114 (112)	25 (6)
	B2	5.7	837 (905)	109 (61)	45 (25)
	IB2	7.9	555 (729)	73 (56)	27 (18)
	B3	9.7	635 (837)	66 (59)	22 (6)
	IB3	11.39	608 (685)	77 (62)	23 (8)
Large	P1	0	351 (254)	61 (27)	67 (15)
	P2	0.5	199 (117)	39 (28)	30 (16)
	P3	1	155 (142)	31 (33)	28 (14)
	B1	2.63	208 (134)	37 (24)	40 (28)
	IB1	4.5	193 (116)	36 (20)	27 (13)
	B2	5.7	338 (39)	48 (10)	46 (26)
	IB2	7.9	371 (358)	57 (69)	21 (14)
	B3	9.7	362 (155)	49 (18)	38 (13)
	IB3	11.39	212 (73)	30 (6)	34 (21)

Table 3.5. Mean (± S.D.) total carbon and nitrogen, mean Mehlich I extractable P in mineral soil samples collected at 0-15 cm depth averaged across all windrow sizes (n=10) for sampling location along the transect (P1 to IB3, 9 locations). Samples were collected in August 2012 at North Carolina.

Location	**Average Distance**	**Mean Total Carbon**	**Mean Total Nitrogen**	**Mean Extractable P conc.**
	---------- m ---------	**------------------- %**	**-------------------**	**----------- µg g^{-1}----------**
P1	0	7.32 (5.18)	0.25 (0.15)	18.8 (6.7)
P2	0.5	6.49 (7.13)	0.22 (0.25)	14.6 (6.1)
P3	1	5.51 (3.50)	0.19 (0.12)	16.0 (12.9)
B1	2.64	5.11 (1.80)	0.17 (0.06)	19.0 (9.5)
IB1	4.5	7.14 (4.58)	0.25 (0.15)	20.9 (15.2)
B2	5.69	4.39 (2.04)	0.14 (0.06)	17.0 (11.6)
IB2	7.9	6.11 (3.68)	0.20 (0.11)	15.0 (7.7)
B3	9.7	4.43 (0.42)	0.14 (0.02)	21.8 (20.7)
IB3	11.38	7.44 (7.48)	0.25 (0.28)	15.4 (12.0)

Table 3.6. Mean (± S.D.) Mehlich I extractable Ca, Mg, and K in mineral soil samples collected from locations P1 to IB3 (9 distances) at 0-15 cm depth along the transects of small (n=3), medium (n=3), and large (n=4) piles in August 2012 at North Carolina.

Pile size	**Location on Transect**	**Mean Extractable Concentration**		
		Ca	**Mg**	**K**
		---------------------(µg/g)----------------------		
Small	P1	70 (27)	19 (7)	42 (8)
	P2	67 (26)	20 (8)	32 (2)
	P3	74 (20)	22 (5)	32 (3)
	B1	36 (22)	12 (5)	23 (7)
	IB1	67 (36)	16 (7)	36 (18)
	B2	19 (2)	7 (1)	23 (2)
	IB2	52 (40)	18 (10)	37 (14)
	B3	42 (23)	15 (5)	33 (2)
	IB3	84 (68)	23 (17)	32 (9)
Medium	P1	132 (48)	35 (13)	66 (19)
	P2	112 (93)	30 (21)	56 (27)
	P3	132 (169)	33 (35)	62 (42)
	B1	102 (138)	22 (23)	43 (25)
	IB1	182 (151)	49 (24)	68 (33)
	B2	52 (29)	18 (9)	40 (7)
	IB2	67 (47)	21 (16)	36 (2)
	B3	115 (109)	26 (17)	50 (18)
	IB3	78 (51)	23 (17)	51 (37)
Large	P1	147 (73)	41 (21)	75 (52)
	P2	113 (123)	24 (17)	52 (46)
	P3	101 (94)	24 (21)	41 (36)
	B1	107 (80)	21 (13)	41 (16)
	IB1	93 (76)	26 (19)	35 (15)
	B2	61 (59)	20 (21)	35 (27)
	IB2	131 (141)	33 (33)	40 (15)
	B3	42 (30)	11 (5)	26 (12)
	IB3	77 (56)	16 (4)	36 (19)

CHAPTER IV

Conclusion

Intensively managed loblolly pine (*Pinus taeda L.*) plantations are an important source of bioenergy production. New federal policies like the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 have been formed to encourage use of renewable transportation fuels (i.e., biofuels), or to require renewable power (i.e. bioenergy) generation (Database of State Incentives for Renewable Energy, 2013). However, higher removal of woody biomass associated with bioenergy and biofuel harvest could result in soil degradation with time and repeated harvests. Due to these new policies and rising concerns about increased woody residue harvests, interest has risen nationwide to update existing biomass harvesting guidelines (BHGs). Seven states including Wisconsin, Michigan, Kentucky, Missouri, Minnesota, Maine and Pennsylvania have already developed new biomass harvesting guidelines. These guidelines recommend leaving varying extents of residual woody biomass on site usually defined as a percentage. The scientific basis for the proposed percentages, however, is quite limited and thus further research is needed to better quantify the impacts of varying levels of woody residual retention on soil quality.

In this study, it was hypothesized that by decreasing the retention of woody residual biomass from 100% to 30 or 15%, or to having no biomass harvesting guidelines, there would be decreases in C and N in the soil surface horizons, and an increase in compaction caused by use of machinery for harvesting and site preparation operations. Since reduced retention of woody residual biomass would also impact the size of windrows and spot piles remaining after site preparation, it was also hypothesized that soil quality indicators like moisture and temperature would be more stable (lower annual variance) near the base of piles as compared to some distance away from piles because of the shadowing effect of piles/windrows and these impacts would increase with increasing windrow/pile size. These more stable conditions should be more favorable for microbial decomposition of organic matter thus there should also be higher nutrient mineralization near the pile/windrow.

This particular study was conducted at sites in North Carolina and Georgia. Each location had four blocks which were further divided in to six treatment plots of varying biomass harvest retention levels. Pre-harvest and post-site preparation forest floor and soil samples were taken at both study sites across all the six biomass harvesting treatments along with bulk density samples. To look at the effect of woody biomass retention at the micro-site level, 10 windrows/piles were randomly selected in both the Georgia and North Carolina study sites. Sampling and data collection was done along a 10-13m transect at the chosen windrows/piles. Overall, there was a large difference in size of windrows and piles, with the smallest windrow size in Georgia being comparable to the largest piles in North Carolina.

The levels of woody biomass retention did not have any significant effect on total mineral soil and forest floor C and N concentration. However, the post-harvest and site preparation C and N concentration in forest floor mass decreased by 16-57 and 3-58 %, respectively. In the mineral soil, C content increased by 34% post site preparation. Bulk density increased by 14.5% from an average value of 1.21 to 1.41g cm^{-3} following harvest and site preparation.

Woody biomass retained in the form of windrows/piles generally increased nutrient concentration near to the base of windrows/piles and concentrations declined going away from the base. However, windrows/pile size did not have any significant effect on soil C, N, Ca, Mg, P, or K concentration at both study sites. Resin capsule extractions showed similar results except for K, which was found to be affected by windrow size at the Georgia sites. Soil temperature, moisture and respiration did not vary significantly with size of the windrow/pile.

This study used large operational plots that were 8-10 ha in size. This design created sampling challenges due to high variability in soil conditions that can lead to difficulty in detecting statistically significant differences. On the other hand, the sampling effort was substantial with over 700 samples collected for one-time measurements at each site and 1000s of samples collected over the repeated measurements. The large operational plots in this study also demonstrated, however, that residue removal of fine woody debris is difficult and costly. Woody residue removal in the absence of biomass harvesting guidelines is incomplete and leaves substantial fine to medium size material on site. As such, woody residue removal at any operational scale may not be sufficient to limit carbon and nutrient recycling to negatively impact soil productivity; that was the case in this study. Existing BHG guidelines followed in many states suggest leaving a percentage of woody residue on site. However, in this study, leaving 100, 30 or 15 % of woody residual biomass on sites did not measurably affect soil quality attributes.