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Switchgrass intercropping reduces soil inorganic nitrogen in a young loblolly pine plantation located in coastal North Carolina

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ABSTRACT

As biofuel production continues to increase, so will demand for forests to provide sources of biomass feedstocks. Intensively managed loblolly pine (*Pinus taeda* L.) plantations cover 15.8 million ha of the southeastern United States. Intercropping of switchgrass (*Panicum virgatum* L.) within loblolly pine stands offers an opportunity to use interbed space to produce an herbaceous biomass feedstock. Furthermore, removal of post-harvest woody residues could act as another forest-based biomass feedstock. Understanding how managing forests for biofuel production influences soil nitrogen (N) cycling and availability is crucial given the critical role N plays in terrestrial ecosystem productivity. Therefore, our objective was to study effects of harvest residue removal and pine-switchgrass intercropping on soil extractable NH_4^+ and NO_3^-. We used a randomized complete block design, consisting of four blocks of seven plots (0.8 ha) established in the summer of 2008 on a recently harvested 34-year-old loblolly pine plantation in the Lower Coastal Plain of North Carolina, USA. Ion exchange membranes were deployed in the top 10 cm of mineral soil starting in June 2009 and replaced continuously every 4–6 weeks through December 2011. Presence of switchgrass significantly reduced soil extractable NH_4^+ and NO_3^-, amounting to a total reduction of 39% and 60%, respectively, over the course of the timeframe (30 months) of this study. There was evidence that intercropping of switchgrass increased extractable NO_3^- in the adjacent pine bed, although this result was only found in the final 6 months of the study. Presence or absence of harvest residues and/or interbed pines in the interbeds generally had no effect on soil inorganic N pools. These results indicate that switchgrass production effectively utilized inorganic N during a time when mineral N supply was greater than N demand by loblolly pines. Assessment of the long-term effects of switchgrass intercropping on soil nutrient cycling and availability and pine health and productivity will be essential to determine environmental and economic sustainability of intercropping.

1. Introduction

Bioenergy production has expanded during the last decade (IEA, 2010), increasing demand for biomass feedstocks. Up to now, most bioenergy has been produced from 1st generation biofuel feedstocks from agricultural crops, such as corn (USDA-DOE, 2005). Forested ecosystems can produce much of the needed biomass for biofuel production, especially in intensively managed forests. Although use of forest biomass for feedstocks is likely to increase, our understanding of the long-term sustainability of intensified bioenergy production from forests is not complete. As of 2010, there were 15.8 million ha of pine (*Pinus* spp.) plantations in the southern United States (Wear and Greis, 2012). Of these plantations, those that are more intensively managed may be able to sustainably produce needed biomass without significant land-use change or diversion of agricultural crops from food production. Forested ecosystems can provide multiple sources of biomass feedstocks, including post-harvest residues or biomass recovered from thinning operations. Furthermore, in southern pine plantations, the growing space between rows of planted trees could be utilized to grow a bioenergy crop, such as switchgrass (*Panicum virgatum* L.) to produce additional biomass for bioenergy feedstocks. Knowledge of long-term sustainability of this novel approach will be essential in order to realize this potential.

Switchgrass has been identified as an environmentally and economically promising feedstock for 2nd-generation biofuel production due to its high productivity, perennial life history and long lifespan, tolerance of a wide range of climatic conditions,

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and low nutrient and water requirements (McLaughlin and Adams Kszos, 2005; Parrish and Fike, 2005; Schmer et al., 2008). Production of an herbaceous biomass from forested ecosystems could diversify economic returns for land-owners and may lead to positive ecological impacts, including increased soil carbon (C) storage and ecosystem N retention (McLaughlin and Adams Kszos, 2005). Woody biomass from forests has also been considered, and extensively studied, as a potential bioenergy source.

Removal of woody biomass, such as post-harvest residues, may alter short- and long-term soil nutrient availability, exacerbating potential plant nutrient limitations and long-term soil productivity. Positive effects of retention of harvest residues or stem-only harvesting on soil nutrient stocks has been shown in many instances (Barber and Van Lear, 1984; Gosz et al., 1973; Hyvönen et al., 2000; Olsson et al., 1996; Tew et al., 1986), but is not always the case (Sanchez et al., 2009; Smethurst and Nambiar, 1990) and depends on the soil type, nutrient of interest, timescale, and intensity of biomass removal. Barber and Van Lear (1984) found that decomposing loblolly pine residues retained a large proportion of initial N and P content, but not Ca, Mg, and K seven years post-cutting. Benefits of retaining harvest residues are likely to occur that may not be detectable if measuring soil and plant responses shortly after site establishment (Barber and Van Lear, 1984; Hyvönen et al., 2000; Smethurst and Nambiar, 1990). Impacts of woody biomass removal on long-term soil nutrient capital in successive rotations, and its relationship to the inherent site nutrient capital, must be considered to determine the sustainability of such practice (Squire et al., 1979, 1985).

An understanding of how increased forest-based biomass extraction influences soil N cycling and availability is important for long-term viability of managed forests. Nitrogen has been identified as the most limiting nutrient to growth and productivity in many terrestrial ecosystems (Vitousek and Howarth, 1991), including loblolly pine forests (Albaugh et al., 2004, 2008; Fox et al., 2007; Jokela and Martin, 2000). Inherent site quality plays an important role in loblolly pine forest productivity, although fertilizers can be applied to help alleviate nutrient limitations and increase productivity. Loblolly pine often responds positively to N fertilization (Albaugh et al., 1998; Amateis et al., 2000; Hynynen et al., 1998), phosphorus (P) fertilization (Gent et al., 1986; Pritchett and Comerford, 1982), and N + P additions (Amateis et al., 2000; Hynynen et al., 1998) depending on the characteristics of a given site. Demand for N and other essential nutrients (e.g., P, potassium (K), calcium (Ca), and magnesium (Mg)), by loblolly pine must be met in order to optimize tree growth (Allen et al., 2005; Fox, 2000).

Competition between planted pines and switchgrass for nutrients may lead to reduced productivity of one or both species without careful soil nutrient management. For example, belowground competition between pine and switchgrass for nutrients or rooting space may have a negative effect on pine growth if switchgrass out-competes pine for these nutrients, especially N (Woods et al., 1992). Nutrient limitations within most loblolly pine forests in the Southeast U.S.A. exist and this limitation is exacerbated by the presence of competing vegetation (Smethurst and Nambiar, 1989). Many studies have shown the negative impact of competing vegetation on pine tree growth and soil and/or foliar nutritional status (Borders et al., 2004; Carter et al., 1984; Gurlevik et al., 2004; Smethurst and Nambiar, 1989; Smethurst et al., 1993; Woods et al., 1992) in other agroforestry systems (Jose et al., 2004). Growth of *Panicum* grasses in young slash pine (*Pinus elliottii* Engelm. var. *elliottii*) plantations significantly reduced pine tree root extension and density and reduced K and P in pine tissues (Smethurst et al., 1993). Suppression of hardwood and herbaceous vegetation at the early stages of stand development increases availability of essential soil nutrients (Gurlevik et al., 2004; Smethurst et al., 1993), which can lead to increased productivity at later stages of stand development (Fox et al., 2007; Lauer et al., 1993; Miller et al., 2003). Therefore, the impact of switchgrass production on N cycling and availability may negatively affect pine productivity if utilization of N by each species overlaps spatially and temporally.

Disparities between soil N availability and tree demand typically occur in young pine stands following harvest as soil N availability is in excess of pine tree demand (Allen et al., 1990; Fox et al., 1986, 2007). Any large disturbance resulting in removal of the overstory vegetation often leads to increased soil N availability (Allen et al., 1990; Fox et al., 1986; Likens et al., 1970; Vitousek and Matson, 1985). As stands develop over time, soil N availability decreases as favorable conditions (e.g., increased soil temperature and soil moisture) for N transformations subside and as plant N uptake increases, eventually leading to possible N limitations in pine (Miller et al., 1976, 1981). This imbalance between N availability and plant uptake has important implications for N cycling in relation to availability to plants and losses from the forest ecosystem. Therefore, it may be possible to utilize increased inorganic N availability to produce a bioenergy feedstock and reduce potential losses of N from the ecosystem during this period of stand development.

Our main objective was to determine the effects of switchgrass intercropping and harvest residue removal on soil inorganic N availability. In particular, we were interested in the ability of switchgrass to reduce excess soil inorganic N in a young loblolly pine stand. We tested two main hypotheses: (1) soil inorganic N concentrations in the surface mineral horizon will be reduced by intercropping of switchgrass between rows of pine; and (2) short-term inorganic N concentrations in the surface mineral horizon are not impacted by the removal of harvest residues. To test these hypotheses, soil NH_4^+ and NO_3^- availability were measured over a 2.5 years period using ion exchange membranes deployed in a recently established field study with treatments reflecting various forest biomass removal and production scenarios.

2. Materials and methods

2.1. Study site and treatments

The Lenoir I Intercropping Sustainability Study site was located in the Lower Coastal Plain physiographic province in Lenoir County, NC (35-12′59″N; 077-26′13″W). Soils were mapped as Pantego (fine-loamy, siliceous, semiactive, thermic Umbric Paleaquults) or Rains (fine-loamy, siliceous, semiactive, thermic Typic Paleaquults) soil series, both of which are classified as deep, very poorly drained soils (USDA Soil Survey, 2013). However, previous site management included installation of ditches (early 1970s) to lower the water table and reduce saturation at the soil surface. Additionally, bedding was used to raise root systems of planted loblolly pine seedlings above the water table, increase soil aeration, and reduce competition. Mean annual temperature at the site ranged from 15 to 21 °C and mean annual precipitation ranged from 1000 to 1500 mm y^{-1}, with a frost-free period of 180–>320 days (Baker and Langdon, 1990; Barrett, 1995).

In summer 2008, four blocks of seven treatments (0.8 ha treatment plots with 0.4 ha measurement plots with a minimum 15 m outer buffer) were established on a recently harvested 34-year-old loblolly pine plantation with a site index of 21.3 m at age 25. A randomized complete block design (RCBD) was used in this study, in which each treatment plot was assigned at random within each of the four blocks. This design allowed for four replicates per treatment. Treatments included: (1) loblolly pine establishment (crop trees planted on bedded rows spaced approximately 6.1 m apart) with harvest residues left in place (i.e., all non-merchantable