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Fertilization and pine straw raking in slash pine plantations: P removals and effects on total and mobile soil, foliage and litter P pools

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ABSTRACT

Pine straw raking and fertilization effects on phosphorus (P) removals, total and mobile P in foliage and straw, and soil extractable P pools, were examined in 15 and 17-year-old slash pine (*Pinus elliottii* Engelm.) stands on soils (an Ultisol and an Entisol) with contrasting nutrient sorption potentials and internal drainage. A factorial study of P fertilization (0, 29, 87 kg P ha^{-1} for two years) and commercial straw raking (no raking vs. annual raking) was used to investigate P removals and changes in total and mobile P pools in foliage, pine needle litter and surface mineral soil. After three years of raking at the Ultisol site, litter in the non-raked plots had approximately 15% more Pi (TCA extractable) than did litter in the raked plots. Raking removed mobile P and broke the P cycle in these stands. Also, pine straw raking depleted extractable soil P, as evidenced by the change in soil P in the surface 10 cm. After five or four raking events, the difference between non-raked and raked treatments ranged from 4 to 11 kg P ha^{-1} at the two sites. An estimate of the number of rakings that would move the sites' surface soil into P deficiency, was linked to the soil's ability to sorb P. These results indicate that Best Management Practices for pine straw raking should include specific P fertilization recommendations to replace depleted soil extractable P, based on raking frequency and the soil sorption capacity.

1. Introduction

In pine plantations of the southeastern United States, pine needles are sometimes raked, baled and sold as pine straw, which is widely used as a landscaping mulch (Duryea, 2000a; Taylor and Foster, 2004; Dickens et al., 2012). Pine straw harvesting is combined with timber production and other land uses to increase revenue (Hayes et al., 2009; Dickens et al., 2011; Dyer and Barlow, 2012; Dyer et al., 2015), and in 2003 represented a $79 million industry in Florida alone (Hodges et al., 2005). Three southern pine species are commercially important for pine straw production; slash pine (*Pinus elliottii* Engelm.), longleaf pine (*Pinus pallustris* Mill.) and loblolly pine (*Pinus taeda* L.) (Dickens et al., 2012). Longleaf pine straw is most favored for its long needles, slow rate of decomposition and color retention, followed by slash pine for similar attributes (Dickens et al., 2011; Dyer and Barlow, 2012).

Standard silvicultural practices for establishing pine plantations can include intensive site preparation, weed control, fertilization and the planting of genetically improved seedlings (Jokela et al., 2010). Soils in the U.S. Coastal Plain tend to be inherently infertile, so nutrient additions are often necessary to optimize growth rates (Pritchett and Comerford, 1982; Fox et al., 2007a). In 2009 nearly 400000 ha of pine plantations were fertilized in the southeastern U.S. (Albaugh et al., 2010).

Although there are well established southern pine forest fertilization programs for enhancing wood production (Jokela, 2004; Fox et al., 2007a,b), specific and cost-effective fertilization recommendations for pine straw production require further development (Dickens et al., 2012). In an early study, Morris et al. (1992) evaluated nutrient removals in commercial pine straw harvests in the Coastal Plain of Georgia. On the basis of nutrient removal rates, they recommended a foliage monitoring program and fertilization at five-year intervals for stands that were raked on an annual basis following crown closure. For stands raked only 2–3 times in a rotation, they suggested that fertilization once or twice during the rotation was sufficient to protect site fertility on most sites.

Commercial pine straw harvesting begins when pine stands are about seven or eight years old (Morris et al., 1992; Duryea, 2000b) and stands are often raked annually, until pines are either thinned or harvested for pulpwood (Dyer and Barlow, 2012). Repeated removals of pine straw interrupt nutrient cycling, potentially depleting site nutrients and reducing stand productivity, thereby threating the sustainability of timber and straw production

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(Morris et al., 1992; Duryea, 2000b; Blevins et al., 2005). Studies in slash pine plantations that examined nutrient removals by raking (Morris et al., 1992; Lopez-Zamora et al., 2001; Susaeta et al., 2012) have shown that raking can remove significant amounts of macro- and micro-nutrients, but amounts depended on site characteristics and raking intensity. Morris et al. (1992) reported that pine straw harvesting operations in Georgia typically rake 75% of the surface area, removing approximately 2800 kg ha^{-1} of pine straw. In such a single harvest, P removals are often low ranging from 0.6 to a maximum of 7.0 kg P ha^{-1} (Morris et al., 1992; Duryea, 2000a; Lopez-Zamora et al., 2001). However, frequent raking can increase removal considerably. For example, Morris et al. (1992) estimated that over an 11 year period, annual raking removed a total of 18 kg P ha^{-1} from a slash pine plantation. These removals exceeded what they had calculated from tree harvesting.

At a site with high inherent fertility, the total annual needle-fall collected by litter traps was 8735 and 9145 kg ha^{-1} in 1994 and 1995, following two annual applications of 280 kg ha^{-1} diammonium phosphate (DAP) (56 kg P ha^{-1}) in 1991 and 1992 (Lopez-Zamora et al., 2001). In 1994 the authors did not find a significant effect of raking or fertilizer application on needle-fall for this Coastal Plain Spodosol; whereas, in 1995 there was less needle-fall in the raked treatments than non-raked treatments. Considering that raking harvests approximately 75% of the stand area (Morris et al., 1992), Lopez-Zamora et al. (2001) estimated 8299 dry kg ha^{-1} yr^{-1} pine straw removal with annual raking. Given the 0.052% needle litter P concentration observed with this treatment, up to 5 kg P ha^{-1} was removed annually. The estimated P uptake rate for slash pine is about 5–8 kg P ha^{-1} yr^{-1} (Adegbidi et al., 2005), which is more than the P removal from annual raking observed in most studies. Duryea (2000a) recommended that pine plantation managers limit raking to only four to five times in a 20-year rotation and that removed nutrients need to be replaced by fertilizer applications.

Specific extractable pools of soil P can be sensitive indicators of changes due to management (Tutua et al., 2013). Soil inorganic P has been reported to decrease from annual raking and increase following DAP applications (280 kg ha^{-1}) in slash pine grown at a Spodosol soil site with high inherent fertility and a high water table (Lopez-Zamora et al., 2001). Reactive inorganic soil P was greater in the non-raked control and plots raked every four years, compared to annual raking or plots raked every two years. In addition, fertilizer treatments resulted in nearly double the total P concentration in pine straw.

Few published studies address nutrient removals with pine straw raking or effects on southern pine stand nutrition (Morris et al., 1992; Duryea, 2000a; Lopez-Zamora et al., 2001; and Susaeta et al., 2012). More information regarding fertilization and raking responses over the range of soil types where commercial pine straw harvesting occurs is also needed to refine Best Management Practices (BMPs) in the Southeastern U.S.

In Florida pine plantations are commonly found on Spodosols, Ultisols and Entisols (Lohrey and Kossuth, 1990). Spodosols can be very poorly to moderately well drained, Ultisols may be very poorly to somewhat poorly drained and Entisols are excessively drained (Jokela and Long, 2012). Current research findings describe pine straw raking effects on the soil chemistry of poorly to somewhat poorly drained sandy soils, but there is insufficient information on effects for excessively drained sandy soils or somewhat poorly drained soils with a high clay content. Our study investigated soil, foliage and pine needle litter P pools in slash pine stands grown on an excessively drained Entisol and a somewhat poorly-drained Ultisol. The study objectives were to: (1) Determine the effects of pine straw removal and fertilization rate on foliar and pine needle litter total P (Pt) and inorganic P (Pi) concentrations and (2) Determine the effect of pine straw harvesting and fertilization on the amount of inorganic and organic Mehlich-1 extractable soil P following fertilization.

2. Materials and methods

2.1. Study sites

This study is a continuation of a previous raking and fertility research project established in 2008–2009 (Minogue et al., 2013). Separate replicated studies were established in mid-rotation slash pine (*P. elliottii* Engelm.) plantations at two locations in north Florida. The first location was somewhat poorly drained and was characterized by a sandy loam surface soil underlying clay loam (Ultisol site). It was located 5 km north of Blountstown, Florida (30°30′N, 85°02′W). The soil series were Dunbar fine sandy loam and Kenansville loamy sand (fine, kaolinitic, thermic Aeric Paleaquults and loamy, siliceous, subactive thermic Arenic Hapludults, respectively) (USDA, 2004). The Ultisol site contained 1.4–6.4% clay, 12.8–18.8% silt and 70.8–80.8% sand in the 0–15 cm depth. Soil texture was analyzed at the Analytical Research Laboratory (ARL) in Gainesville, Fl. In the period 2009–2012, mean annual air temperature was 18.0–19.4 °C and mean annual precipitation was 1053–1656 mm (FAWN, 2014). The slash pine plantation at this location was established in winter 1997. The site index was 24.4 m at base age 25 years. In 2008, the pre-treatment average wood volume was 195 m^3 ha^{-1}, average tree diameter at breast height was 16 cm, and tree height was 12 m (Minogue et al., 2013).

The second location had excessively drained, deep, sandy soil (Entisol site) and was located 20 km west of Live Oak, Florida (30°18′N, 83°12′W). The soil series was Alpin fine sand (thermic, coated Lamellic Quartzipsamments) (USDA, 2006) with 91.6–95.2% sand, 0.4–2.4% clay and 4.4–6% silt at 0–15 cm depth. Soil texture was analyzed at ARL. In the period 2009–2012, mean annual temperature was 18.4–20.3 °C and mean annual precipitation was 1114–1451 mm (FAWN, 2014). The slash pine plantation on this site was established in winter 1995. The site index at this location was 20.8 m, at base age 25 years. In 2008, the pre-treatment average wood volume was 149 m^3 ha^{-1}, tree diameter at breast height 13 cm and tree height 12 m (Minogue et al., 2013).

2.2. Experimental design and treatments

During establishment of the initial research project at each study site (Minogue et al., 2013), twenty four 0.2 ha treatment plots were selected for uniformity in forest stand and soil conditions to test eight treatments assigned in a completely randomized factorial design with three replications. Response variables were assessed within a 0.03 ha measurement plot, centered within each treatment plot, to provide adequate treatment buffers. The initial study was designed to test the effectiveness of Florida Silviculture BMPs by evaluating the fate of applied N and P from a single source, diammonium phosphate (DAP), in two sequential annual early spring fertilizations, with and without annual winter pine straw harvesting. Four levels of DAP were applied: 0, 144, 430 and 718 kg ha^{-1}, which provided up to 258 kg ha^{-1} N (near the three-year maximum 280 kg ha^{-1} BMPs limit) and up to 291 kg ha^{-1} P (in excess of the three-year maximum 90 kg ha^{-1} BMPs) (Anonymous, 2008). For the objectives of this study, treatments included the three lower levels of P fertilization (0, 58, 174 kg P_2O_5 ha^{-1}) with and without annual winter pine straw raking (Table 1). Fertilization rates provided 0, 29 or 87 kg ha^{-1} elemental P at each of two sequential annual fertilizations in 2009 and 2010. This study quantified total and mobile P concentrations in pine foliage and pine needle litter, soil total and extractable P,