LONG-TERM AFFECTS OF A SINGLE P FERTILIZATION ON HEDLEY P POOLS IN A SOUTH CAROLINA LOBLOLLY PINE PLANTATION

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Abstract—While phosphorus (P) fertilization increases plant available or "labile" P immediately after fertilization, it is uncertain how it influences P pools over the long term in forest soils. Phosphorus pools from a 22-year-old loblolly pine (*Pinus taeda* L.) fertilization study were quantified using the Hedley sequential fractionation procedure, Mehlich-1, and Mehlich-3 soil tests. The Hedley fractionation procedure partitions the extracted P into six fractions, which are then defined as labile, moderately labile, and recalcitrant P pools. After 22 years, fertilization effects were limited to the surface horizon. The largest response to fertilization in this study was an increase in the Hedley recalcitrant P pools in the 0 to 10 cm soil horizon. Mehlich-3 extractable P was significantly ($p = 0.02$) larger in the 0 to 10 cm soil horizon of the fertilized treatment compared to the control. Our results suggest the largest portion of applied P has remained in the surface soil horizon and has the potential to increase site quality.

INTRODUCTION

Plant growth is typically limited by nitrogen (N) and P availability in forests soils. While the absolute quantities of these nutrients in forests soils may be large and appear sufficient to support robust plant growth in some locations, the actual pools of labile P are markedly smaller and typically growth limiting. The simple and economically viable solution in agriculture and plantation forestry operations has been to apply inorganic fertilizers to meet plant growth requirements. In 1999 nearly 500 000 ha of pine plantations in the Southeastern United States were fertilized with P or a combination of P with N (NCSFNC 2000). Whereas inorganic N can be volatilized and rapidly lost from the site after fertilization, the fate of inorganic P (Pi) and organic P (Po) is typically considered to be regulated by plants, soil microbes, and the P fixation capacity of the soil (Turner and Lambert 1988, Yuan and Lavkulich 1994).

The affects of P fertilization on the long-term P cycle in forest soils has recently been investigated in pine plantations in the Southeastern United States. Fertilization can increase plant uptake of P and the total P concentrations in litterfall up to 400 percent (Dalla-Tea and Jokela 1991, Piatek and Allen 2001). Several studies have shown that the O horizon may be a sink for P in forest soils due to an accumulation of P over time (Piatek and Allen 2001, Sanchez 2001). Comerford and others (2002) sampled plant and soil responses to a single P application of 17.5 kg-P/ha, 29 years after fertilization. Their results supported the view that P fertilization increased the pine needle litter P content, and increased labile pools P from easily mineralizable Po.

In the early 1980s a large number of silvicultural research trials were established to examine interactions among site preparation, weed control, and fertilization. The short- and medium-term growth response to a single P treatment of 56 kg/ha applied as 280 kg/ha DAP showed increases in stand growth in excess of 100 percent on many sites (NCSFNC 2004). Determining the fate of the applied P may elucidate the long-term affects of P fertilization on labile P pools. A significant and long-term increase in labile P pools may positively affect the following rotation's growth thereby reducing the need for increasingly expensive fertilizers applications and improving forest site quality.

There are a variety of methods to test for biologically available or "labile" P depending largely upon the physical and chemical properties of the soils you are testing (Pierzynski 2000). Routine soil tests such as Mehlich-1 (M-1), Melhich-3 (M-3), and Olsen-P use a variety of different chemicals to predict labile P pools (Tiessen and Moir 1993). The results of these tests are correlated with plant growth experiments that predict critical levels of P pools to meet agronomic crop needs. These equations typically account for 50 to 60 percent of the observed variability in crop growth (Tiessen and Moir 1993). While these empirically derived equations work well in agronomic crops they may be less reliable in forested ecosystems where biogeochemical cycling of P is more important and long rotation cycles limits their usefulness.

The Hedley sequential fractionation procedure attempts to quantify P pools within a soil by using a sequential chemical fractionation (Hedley and others 1982). The Hedley fractionation procedure has the advantage over most routine soil tests in its attempt to measure Po and Pi pools. These Po and Pi pools are then partitioned into labile, moderately labile, and recalcitrant P pools based upon to the chemical strength of the P bonds and the plants ability to access those P pools (Hedley and others. 1982, Tiessen and Moir 1993).

Our long-term goal is to have site specific, whole rotation, nutrient management recommendations for loblolly pine plantations. To attain this goal we need to understand the long-term effects of management practices on labile P pools. The specific objectives of this research project are to quantify the effects of fertilization on the Hedley P pools in loblolly pine plantation soils. Our hypotheses are that 20 years after fertilization:

Ha: Hedley labile P pools in the fertilized plots will be significantly greater than control plots.

Ha: Hedley moderately labile organic P pools in the fertilized plots will be significantly greater than control plots.

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Citation for proceedings: Stanturf, John A., ed. 2010. Proceedings of the 14th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-121. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 614 p.

MATERIALS AND METHODS

Field Experiment

Treatment plots sampled in this study were established in a loblolly pine plantation in Williamsburg Co., SC (SC1101). The SC1101 site was planted in March 1979 and fertilized with 56 kg-P/ha applied as 280 kg-DAP/ha in April 1979. All trials were installed with four blocks based on uniformity of soil and site conditions. Treatment plots were 20 by 20 meters, with 16 rows of 16 trees planted at 2.4 by 2.4 meter spacing. The internal 8 rows by 8 trees served as the measurement plots. The site is located on a Wahee soil series (Aeric Endoaquults) in the coastal plains physiographic province. A factorial combination of two levels each of site prep, fertilization, and vegetation control were applied. The eight treatments were applied in a split-plot design with site preparation assigned the whole plots treatments. The subplot treatments were fertilization and weed control. A description of treatment applications and soil horizons sampled for this study is listed in table 1.

P Pools Assessment

Soil samples were collected within the plots in 2001 using a 7.2-cm-inside-diameter probe. Phosphorus pools were extracted from the 0 to 10 and 10 to 20 cm depths. The samples were sieved (< 2 mm) to remove coarse debris, air dried, and stored in plastic bags until analyses. The soil samples within each plot were again passed through a 2 mm sieve and composite samples were analyzed for Hedley P content following the procedure of Tiessen and Moir (1993). Mehlich-1 and M-3 extractable P were also quantified (Pierzynski 2000). Subsamples of the composites were oven dried weigh and moisture corrections. Three lab replicates were analyzed per composite samples.

Hedley sequential fractionation—The Tiessen and Moir (1993) adaptation of the Hedley sequential fractionation procedure uses six extracting solution of differing ionic strength to divide the P content into pools of decreasing biological availability (fig. 1). The six sequential fractions are (1) deionized water with an anion exchange membrane-P; (2) $NaHCO_3$-Pi and -Po; (3) NaOH-Pi and -Po; (4) 1M HCl-P; (5) hot concentrated HCl-Pi and -Po; and (6) H_2SO_4/H_2O_2-Pi which when summed give Total Hedley P. Readers should refer to Tiessen and Moir (1993) for a detailed description of the fractionation procedure.

Methods of Analysis

Statistical analyses were performed using the MIXED model with restricted/residual maximum likelihood estimation method for a split-plot design in SAS software (SAS Institute, Cary, NC). The Satterthwaite option was employed to calculate the correct degrees of freedom. When necessary, data was natural log transformed, when appropriate, to meet the model assumptions. Generalized least squared means were calculated and analyzed for treatment effects at the $p < 0.05$

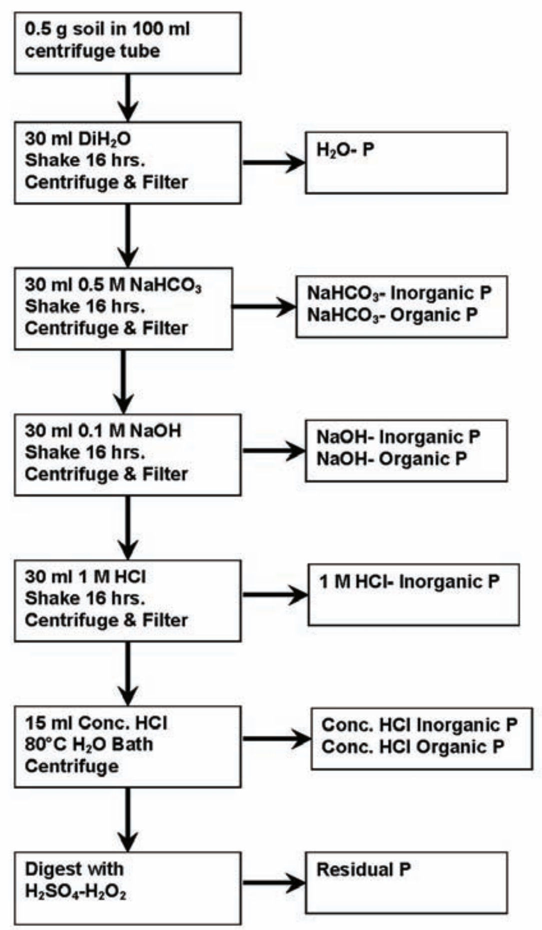

Figure 1—Schematic representation of the Tiessen and Moir (1993) modification of the Hedley sequential fractionation procedure.

RESULTS AND DISCUSSION

The Hedley labile P, Mehlich-1, and Mehlich-3 extractable P pools were largest in the surface horizon and fertilized treatment (table 2). Hedley labile P pools are slightly larger in the surface horizon of the fertilizer plots compared to the

Table 1—Silviculture treatments and soil depths sampled for quantification of Hedley P pools. Treatment chosen exhibited the largest growth response 14 years after fertilization a. i. = active ingredient

Treatment	Site Prep	Fertilizer (kg-P/ha)	Weed Control (kg-hexazinone/ha)	Soil Depth (cm)
Control	Chop	0	0	0 - 10
Fertilized	Chop, Bed	56	1.12	10 - 20

Table 2—Summary of Hedley P pools, Mehlich extractable P pools, from the 0-10 cm soil horizon of a SC loblolly pine plantation. Treatments were 0 or 56 kg/ha P applied at establishment. Values in parenthesis represent standard error of the means

Extraction	Treatment (P mg/kg)		Difference %	Contrast p-value
	Control	Fertilized		
Mehlich-1	5.3	7	32	*
Mehlich-3	49.4(1.16)	80.9 (1.16)	64	p = 0.005
Hedley Labile P	9.6 (0.71)	11.5 (0.28)	19	p = 0.096
Hedley Mod. Labile P	1.8 (1.3)	3.53 (1.3)	98	p = 0.059
Hedley Recalcitrant P	45.3 (4.8)	59.6 (4.9)	31	p = 0.039
Total Hedley P	56.8 (5.9)	74.7 (5.8)	31	p = 0.217

*Mehlich-1 was performed on a simple composite soil sample.

control plots (p = 0.096, table 2). This is supported by the increase in Mehlich-1 and Mehlich-3 extractable P pools in the fertilized plot (fig. 2). Both Mehlich-1 and Hedley labile P pools are measured by relatively mild extracting solutions which would be measuring P loosely sorbed to the mineral soil and Po compounds. Mehlich-3 extractable P was significantly higher (p = 0.005) in the fertilized treatments (table 2). Mehlich-3 uses a stronger extracting solution which, in comparisons to the Hedley fractions, appears to be liberating Pi from the more recalcitrant P pools (fig. 2).

Hedley labile P is extracted by the first two fractions (DiH_2O and $NaHCO_3$) and is readily absorbed by plants and microbes (Tiessen and Moir 1993). Anion exchange membranes first remove the Pi held in soil solution. The P extracted by the bicarbonate solution represents P that would be exchanged because of HCO_3^- generated from root respiration. These two pools of phosphorus are believed to represent the labile phosphorus pools (Cross and Schlesinger 1995, Johnson and others 2003, Tiessen and Moir 1993).

Hedley moderately labile P nearly doubled in the fertilizer treatment to 3.53 mg-P/kg-soil (table 2). While the increase confirmed our hypothesis, it makes up a very small portion of the extractable Hedley P (fig. 2). The Hedley moderately

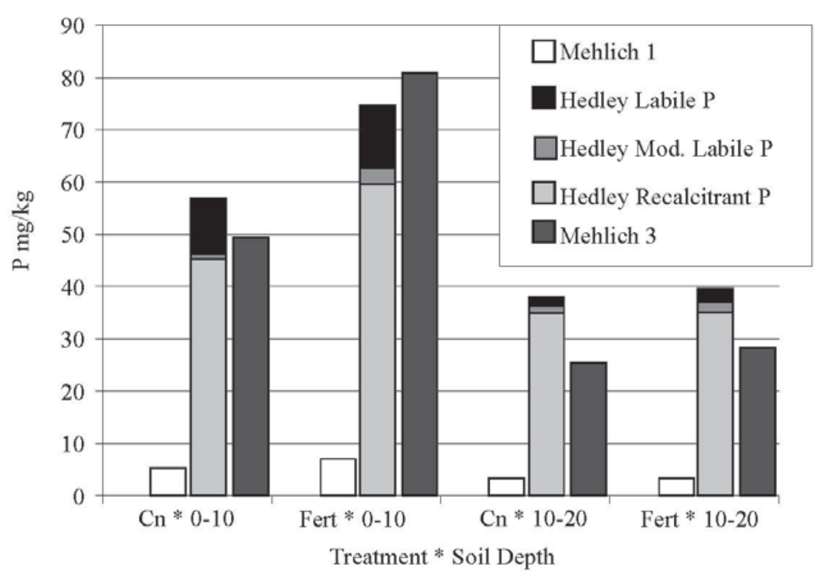

Figure 2—Mehlich-1, Mehlich-3, and Hedley extractable P pools from a SC loblolly pine plantation 22 years after a single fertilizer application of 280 kg/ha DAP. Treatments were 0 or 56 kg/ha P applied at establishment.

labile P pools are composed of the NaOH-Po and 1 M HCL fractions (Tiessen and Moir 1993). The NaOH-Po pool is believed to be involved in the long-term transformation of P pools but may be plant available over several years to decades. The Pi extracted from 1 M HCl is likely calcium associated Pi (Tiessen and Moir 1993). In acid forest soils it is likely generated in part from decomposing soil organic matter.

The Hedley recalcitrant P pool had the largest increased 22 years after fertilization to 59.6 mg-P/kg-soil (fig. 2). This was largely driven by an increase in NaOH extractable Pi ($p = 0.025$) and represent P bound to the Fe- and Al- oxides. When Pi is brought into soil solution, it is an anion that can be rapidly and strongly adsorb to soil Fe- and Al- oxides. The Pi anion can also be rapidly immobilized by plants or soil microbes. Therefore changes in Hedley P pools do not necessarily follow a sequential order. For example labile P may not be converted to moderately labile P which would in turn be converted to recalcitrant P.

The Hedley recalcitrant P pools include the 0.1 M NaOH-Pi, hot concentrated HCl, and the concentrated H_2SO_4/H_2O_2 fractionations (Cross and Schlesinger 1995). The P pools extracted by these solutions are believed to be highly recalcitrant and thought to be unavailable to the plant. However recent studies have shown changes in these pools attributed to plant or microbial uptake (Gahoonia and others 2000, Liu and others 2004, Liu and others 2006). These recalcitrant P pools may be made labile with the exudation of organic acids like oxalate from plant roots and soil microbes. These organic acids can release P from the Hedley recalcitrant P pools by increasing the solubility of P in the soil solution (Fox and Comerford 1992).

CONCLUSION

The Hedley fractionation procedure attempts to extracts P, based upon chemical solubility, into pools believed to have biological relevance. However, recent research has shown moderately labile and recalcitrant P pools are indeed accessible to the soil biota. Therefore interpretation of Hedley extractable P pools have been further complicated. Twenty-two years after fertilization all three soil tests showed an increased in labile P pools in the surface (0-10 cm) soil horizon. There was also a small increase in the Hedley moderately labile P pools. However, the fertilizer applied has been largely sequestered in the Hedley recalcitrant P pool. The increase was largely Pi associated with Fe- and Al-oxides. In light of recent research this does not preclude the potential that a portion of this P pool may be plant available for the following rotation.

Future research should be directed towards quantifying the long-term affects of fertilization on organic P species present using NMR. Additional research could monitor changes in Hedley P pools after harvesting operations.

ACKNOWLEDGMENTS

Funding for this research was provided by the USDA NRI Competitive Grant Program. We would like to thank Lance W. Kress (U.S. Forest Service, Southern Research Station, Forest Genetics and Biological Foundations) for collection of the soil samples.

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