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Pinus taeda carryover phosphorus availability on the lower Atlantic Coastal Plain

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ABSTRACT

Phosphorus (P) fertilizer that remains in the soil after harvest and into the subsequent rotation is referred to as carryover P. Carryover P is not well understood in loblolly pine (P. taeda) silviculture, especially on highly P responsive sites, where this effect could potentially have the greatest benefit to land managers. Our study aims to determine the duration of the P carryover effect and the magnitude of response to soil P as it relates to previously applied P fertilizer rates from the previous rotation. To address this knowledge gap, we studied two highly weathered sites on the lower Atlantic coastal plain: a somewhat poorly drained Spodosol and a poorly drained Alfisol over three years from pre- to post-harvest. Two years post planting, carryover fertilizer treatments resulted in a 13% increase in height for the 121 kg P ha-1, a 15% for the 81 kg P ha-1, and a 17% increase for the fertilized 40 + 45 kg P ha-1 treatments compared to the control for the Alfisol. Spodosols appeared to respond to any additional fertilization compared to the control group regardless of rate. Importantly, we found that O horizon mass and P content from the first rotation, approximately seven years before harvest, exhibited a positive linear relationship with one-year-old heights in the Spodosol and one- and two-year-old heights in the Alfisol. These findings shed light on the importance of the O horizon characteristics and its potential as an indicator for tree growth in subsequent rotations.

1. Introduction

Phosphorus (P) fertilization in loblolly pine (*Pinus taeda* L.) plantations benefits overall tree productivity in P-deficient soils (Pritchett and Swinford, 1961; Gent et al., 1986). Many of these P-deficient soils are common across Lower Atlantic Coastal Plain in the southeastern United States and consist primarily of highly weathered Ultisols, Spodosols, and Alfisols. These soils are sandy, acidic, and dominated by 1:1 clay layers with high P adsorption capacities (Everett and Palm-Leis, 2009) and are inherently P deficient due to the depletion of P in the parent material over time (Vitousek et al., 2010; Comerford et al., 2002). Due to these limitations, these soils are hypothesized to be in a "terminal steady state" of P depletion as the parent material is slowly depleted of P requiring additional amendments to maintain optimal growth rates (Walker and Syers, 1976). Today, in high-intensity silviculture, P is applied one to three times over 25 years on a single full plantation rotation, with cumulative rates typically ranging from 18 to 40 kg ha^{-1} P. Without these amendments, the primary source of available P for these soils originates from organic matter decomposition and mineralization of the forest floor (Comerford et al., 2002). In highly weathered acidic soils, this P fertilizer is rapidly converted from labile to nonlabile adsorbed to amorphous Al and Fe oxides (Pierzynski et al., 2005). Sorption of inorganic P onto these Al and Fe complexes in these systems is a significant sink for P in these forest systems (Comerford and de Barros, 2005). The sorbed P is released from these amorphous complexes via organic acids such as citrate, oxalate, and other phosphatases released by the rhizosphere or by ectomycorrhizal fungi that associate with the roots of the trees (Plassard et al., 2011; Harris et al., 2010; Fox and Comerford, 1990).

Because most of the P in these soils are present in fixed organic forms or inorganic forms adsorbed onto mineral complexes, *P. taeda* was discovered to be highly responsive to P fertilization on these sites when applied (Gent et al., 1986; Amateis et al., 2001). Once it was realized that these soils could produce quality wood products with a modest

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application of P, fertilization on these sites increased dramatically. *P. taeda* plantations have been fertilized with P since the late 1960 s, with peak applications of P in 1999, with approximately 316,059 ha fertilized across the southeastern region (Gent et al., 1986; Pritchett and Llewellyn, 1966). By 2016, P fertilizer alone was applied to only 46,439 ha at site establishment across this same region (Albaugh et al., 2019), only 14% of the total applied in 1999. The decrease in P application can be partly attributed to increasing fertilizer costs and evidence that a single P amendment applied at planting of 28 kg ha^{-1} P can maintain a highly productive *P. taeda* stand for up to 20 years or more during a single rotation on highly weathered Ultisols (Pritchett et al., 1982; Turner and Lambert, 2002). Due to the longevity of response from a single application of P, significant interest was generated regarding the carryover potential of residual P fertilizer into a subsequent rotation (Everett and Palm-Leis, 2009; Comerford et al., 2002). The P carryover effect refers to residual P fertilizer carried over from one rotation to another. Quantifying the carryover effect to reduce the need for fertilizer is commonplace in agricultural systems with annual crop rotations (Doydora et al., 2020), but little research has been conducted in production forestry (Ballard, 1978; Comerford et al., 2002; Crous, 2007; Turner and Lambert, 1986). Only one study has been performed on *P. taeda* plantations on the Lower Atlantic Coastal Plain in the southeastern United States (Everett and Palm-Leis, 2009).

Determining how much P carries over into the subsequent rotation is not as simple as collecting soil samples after harvest due to the assart effect (Kimmins, 1987). The assart effect is a transient increase in available nutrients caused by significant disturbance effects such as site preparation and harvesting (Kiser and Fox, 2012). The additional mobilization and release of P from this effect could lead managers to overestimate the available P in the system. The assart effect is caused by the rapid decomposition of organic material into subsurface horizons by a disturbance, aerating the soil and increasing the respiration rates and mineralization of organic material (Kimmins, 1987). The extent and magnitude of this effect are hypothesized to change depending on environmental conditions and the previous rotation's P fertilization rates (Fox et al., 2011). However, our current knowledge of this effect on *P. taeda* is limited to a single poorly drained Albaquult in the southeastern United States (Everett and Palm-Leis, 2009). This effect highlights the importance of the forest floor and its relationship to P cycling in these systems and helps explains why a single P application in these sites can persist for up to 20 years after application. A more comprehensive study of the P carryover effect and the associated assart effect is needed to predict carryover responses under other soil types, textures, drainage, and environmental conditions.

Foliar P testing is used to assess P deficiencies in forest plantations directly and is usually a strong indicator of response to P fertilization (Everett and Palm-Leis, 2009). Due to its widespread adoption for testing P deficiencies in *P. taeda*, a widely accepted P concentration of 0.10% P has been used for over 40 years as the critical value before deficiency symptoms manifest (Ballard, 1980; Pritchett, 1968; Wells et al., 1973). The optimal soil test for P varies depending on which P pool is being targeted and the characteristics of the soil itself. Mehlich 1 and Mehlich 3 (M3P) soil extracts are widely used in agriculture and forestry on acidic soils in the U.S. to recommend fertilizer amendments (Mehlich, 1984). Critical values for Mehlich 1 and M3P extractions for *P. taeda* plantations are five ppm and ten ppm, respectively (Wells et al., 1986). M3P extracts inorganic and organic forms of P from the soil (Cade-Menun et al., 2018) and is quantified colorimetrically or by inductively coupled plasma spectrometry (ICP). These methods quantify orthophosphate in solution. However, ICP also quantifies inorganic and organic P forms that may not have been plant-available (Cade-Menun et al., 2018; Fox et al., 2011), potentially providing inaccurate estimates for plant P availability. M3P soil extracts are also limited temporally and require multiple samplings to track soil P concentrations over time in perennial crop systems.

Anion exchange resin probes offer an alternative and potentially better predictor of productivity to traditional soil extraction methods for measuring available soil P (Van Raij et al., 1986). These probes offer a solution to M3P soil extractions, which extracts labile and non-labile P compounds from a single time-point by creating a sink for only labile P, acting as a potential analog to a tree root. Anion resins passively adsorb solution phase P (resin-P) to estimate labile P (Qian and Schoenau, 1995; Schoenau et al., 1993). These probes have been used in modified Hedley sequential fractionalization procedures as the first step to extract the available soluble P fraction in the soil as PO_4^{3-}, $H_2PO_4^-$ and HPO_4^{2-} (Tiessen et al., 1993). The resin creates a diffusive sink for P, which is saturated with a counter ion. Most resins are saturated with HCO_3^- which desorbs readily into the soil and biologically mimics rhizosphere respiration (Qian and Schoenau, 2002). Resin probes have proven applications in agriculture, forestry, and ecology to measure resin-P from various ecosystems (Tejowulan et al., 1994; Meason et al., 2009; Karamanos et al., 2013; Meason et al., 2009). Unfortunately, field calibration databases are lacking to interpret these results effectively across variable soils, environments, and crops. Considering the widespread applications of these resins, we would like to see a wider adoption of resins to expand the knowledge base surrounding this method in production silviculture.

Our experiments aimed to distinguish the two factors influencing the need for fertilization at planting: the growth response of *P. taeda* based on soil P build-up in the first rotation and the identification of soil tests and conditions that best represent this build-up for each site (Ballard, 1978; Comerford et al., 2002; Crous et al., 2007; Everett and Palm-Leis, 2009). The experiment has two primary objectives: 1) determining the extent of height responses in *P. taeda* resulting from the P carryover effect, and 2) evaluating P availability indicators (M3P concentration, foliar P, and resin-P concentrations, and O horizon P content) in two distinct sites within the Lower Atlantic Coastal Plain and examining their relationship with height growth.

2. Materials and methods

2.1. Site description and study design

This experiment utilizes plots established from a previous regional study on nitrogen (N) and phosphorus (P) fertilization rates conducted by the Forest Productivity Cooperative between 1998 and 2001 (Tacilla Villanueva, 2015). The original regional experiment investigated the growth response of juvenile *P. taeda* plantations to N and P applications across various site conditions in the southeastern United States. This paper focuses on two sites selected from the original study, which were responsive to P fertilization, represented two distinct soil taxonomies, represented a large area in the region, and were within proximity to one another. Each treatment was planted using elite containerized closed pollinated seedlings with six rows and 12 trees per row for 72 trees per treatment on 0.1 ha plots. Individual tree heights, root collar diameter, and mortality were collected for each measurement plot in the first two years of growth for each site. Trees were measured using a height pole in January 2021 and January 2022, approximately 1 and 2 years after establishment, and root collar diameter was measured using a caliper. At this early stage in growth, tree height and root collar diameter were highly correlated; therefore, tree height was used as our indicator for P responsiveness across the following analyses.

The previous experiment, referred to in the text as the "first rotation," was harvested in 2019 and established in 1998 for the Spodosol and in 1999 for the Alfisol at stand age 5 and 3, respectively. The experimental treatments in the first rotation were arranged in a randomized complete block design with four replicates for each treatment. These treatments consisted of hand broadcasted N applications, of rates from 404 kg N ha^{-1} to 1210 kg N ha^{-1}, applied as urea every 2, 4, or 6 years over twelve years from 1999 to 2011). Fertilizer P was applied at the establishment of the study (age 5 Spodosol, age 3 Alfisol) at a rate of 10% of the total cumulative amount of N applied, using hand-broadcasted triple superphosphate. The current rotation, referred to in the text as the "second rotation," was established on the same plots as the first rotation after harvest. In the second rotation, treatment plots were divided based on P application rate from the first rotation (carryover rates) and whether plots would receive an additional 45 kg P ha^{-1} hand-broadcast applied triple superphosphate (re-fertilized) to mimic current operational conventions (Table 1, Fig. 1). The cumulative P rate for the two rotations is expressed as X + Y, where X represents the rate of P in the first rotation, and Y represents the rate of P in the second rotation. Additionally, all treatments in the second rotation received an additional 52 kg N ha^{-1} as urea with a urease inhibitor, 29 kg K ha^{-1} as KCl, and a micronutrient mix P. As part of the site preparation for weed control, all treatments in the second rotation received 0.18 L of Arsenal© herbicide after bedding in the spring. For the second rotation, all plots and treatments received hand-broadcasted fertilization of NPK and micros at planting.

The first site, located in northeast Florida, features poorly drained soil with a fine, mixed, active, thermic Typic Albaqualf (Meggett series) profile. The parent material consists of marine sediment, and the soil includes an argillic horizon (Fisher and Garbett, 1980). The second site, in southeast Georgia, is somewhat poorly drained and exhibits a sandy over loamy, siliceous, active, thermic Typic Haplohumods (Leon series) soil profile. The parent material is also marine sediment, and the soil contains multiple spodic horizons without an argillic or kandic horizon within the top 100 cm of soil depth (Table 2). Soil properties, including drainage class, texture, depth to subsurface layers, and site physical and chemical properties, were collected in 2013 during the first rotation (Table 3).

2.2. Foliar P collection

Foliar P was analyzed in years one and two and will continuously be monitored each year until the experiment's termination at the end of the rotation. Foliar P was determined by collecting 100 first flush fascicles from a primary branch each winter from five height-dominant trees after one year of growth to assess potential stand productivity (Albaugh. et al., 2010). The samples were combined into a single sample and dried before analysis at 65–70 °C to a constant weight. Foliar concentrations were determined using ICP analysis for N, P, K, and micros.

2.3. Anion extractable resin probes

Resin probes were deployed in a subset of field treatments to measure resin-P due to the cost and logistics of installing and removing the probes. The subgroup used to measure resin-P contained the following treatments: 0 + 0 P, 40 + 0 P, 60 + 0 P, 40 + 45 P, and 121 + 0 P. The subgroup of treatments was chosen to provide a range of possible P amendments. Fertizion with P at planting for the 40 + 45 P treatment was applied shortly after probe installation. All probes were installed after planting in the winter of 2019 to assess nutrient supply rates and dynamics. Seven 90-day burial periods were analyzed from the sites, with the last extraction in the fall of 2021. A 90-day burial period was chosen based on the known nutrient limitations for the site due to the low acid-extractable P concentrations found in each soil. Probes were isolated from plant roots using 25 cm diameter by 30 cm deep PVC collars (open on top and bottom) to prevent roots from penetrating the resins and nutrient uptake. Four pairs of probes were installed in each plot (Figs. 1 and 2). Two pairs were placed between the planting rows (interbed) and two within tree rows (bed). After each 90-day burial period, probes were extracted from PVC collars, washed, and placed into labeled Ziploc® bags. The probes were returned to Western Ag Innovations Inc., Saskatoon, SK, for further analysis. All probes were eluted with 17.5 mL of 0.5 mol L^{-1} HCl per probe for one hour. Inorganic N (ammonium and nitrate) in the eluant is then determined colorimetrically using automated flow injection analysis using a Skalar San + Analyzer (Skalar Inc., Netherlands). The remaining nutrients (P, K, S, Ca, Mg, Al, Fe, Mn, Cu, Zn, and B) were measured using inductively coupled plasma (ICP) spectrometry (Optima ICP-OES 8300, PerkinElmer Inc., USA). All standards and controls were prepared in a 0.5 mol L^{-1} HCl matrix equivalent to that of the samples.

2.4. Mineral soil and O horizon sampling

Two composite soil samples, consisting of eight 15 cm soil cores, were collected from each treatment replication from each site once a year over a three-year timespan from January 2020 through May 2022 from the bed and interbed of each treatment plot. Soil samples were air-dried, ground, and sieved using a 2 mm mesh. These soil samples were then analyzed using the M3P soil extraction method and analyzed using ICP. O horizon samples were collected and analyzed for P content between May and June 2013, approximately 13 years after the P fertilization treatment in the first rotation. The O horizon, including twigs and small branches less than 2.5 cm in diameter, was sampled at four locations chosen via random quadrat sampling in each plot with a 0.25 m^2 frame. The four subsamples were composited for each plot. Total P concentration in the O horizon was determined by dry-ashing 0.5 g at 500 °C and dissolving the ash in 10 mL of 6 N HCl solution and 40 mL of deionized water. P in solution was analyzed as described by Hansen et al. (2013) on a Varian Vista MPX Inductively Coupled Plasma atomic emission Spectrophotometer (ICP-AES, Varian, Palo Alto, CA, USA). Total P content was determined by multiplying P concentration and O horizon mass (Fig. 3).

2.5. Statistical analysis

Treatment differences among tree heights, tree height increment

Table 1
Treatments and cumulative rates of applied fertilizer for the first and second rotations. The first number under the "P fertilization treatments" column represents P applied from the first rotation in kg ha^{-1}, and the second number represents the amount of P in kg ha^{-1} applied in the second rotation. All treatments received NPK in the first rotation and N and K in the second rotation, but only select treatments received P. X + Y, where X = the first rotation rate and Y = the second rotation rate.

P Fertilization Treatments	First Rotation (X)		Second Rotation (Y)		
	Cumulative P	Cumulative N	Cumulative N	Cumulative K	Cumulative P
	kg ha^{-1}				
Carryover Treatments					
0 + 0 P	0	0	52	29	0
40 + 0 P	40	400	452	29	40
60 + 0 P	60	600	652	29	60
81 + 0 P	81	807	859	29	81
121 + 0 P	121	1210	1262	29	121
Re-Fertilized Treatments					
40 + 45 P	40	400	452	29	85
60 + 45 P	60	600	652	29	105
81 + 45 P	81	807	859	29	126

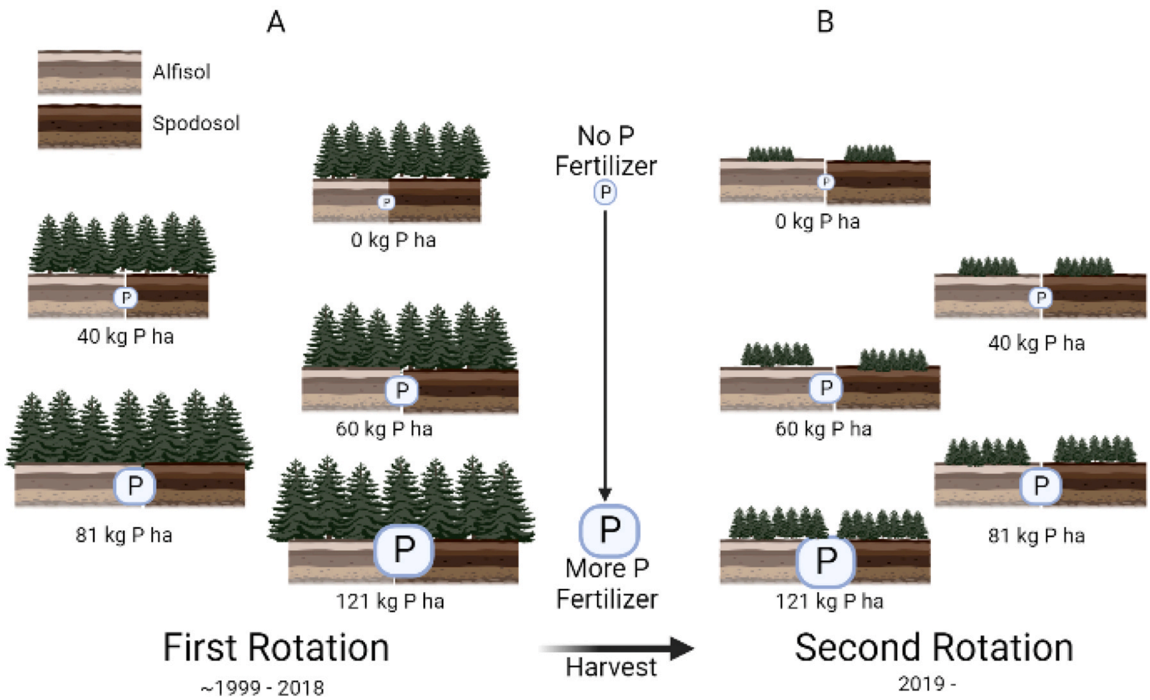

Fig. 1. Graphical representation of first and second rotations showing the increased magnitude of P fertilization carrying over into the second rotation.

Table 2
Location, soil, and forest stand properties from each site tested from the first rotation. Note: The Alfisol study was established at a standard age of three, and the Spodosol was established at age 5.

Site	Location	Parent Material	Soil Taxonomy	Species	Drainage	Study Establishment	"Base" Site Index*	Year Since P Fertilization	Harvest age (2019)
First rotation 1998 – 2019									
Alfisol	Nassau, Florida (30.6661, −81.8361)	Flatwoods	Fine, mixed, active, thermic, Typic albaqualf	*Pinus taeda*	Poorly	1999	45	21	26
Spodosol	Brantley, Georgia (31.3353, −81.8217)	Flatwoods	Sandy, siliceous, thermic grossarenic alaquods	*Pinus taeda*	Somewhat Poorly	1998	67	22	25

[*] Base Site Index at 25 years old prior to study establishment | Source: Official Soil Series Description – USDA NCRS Soil Survey Division and the University of Florida IFAS Extension

Table 3
Physical and chemical soil properties of the Spodosol and Alfisol, collected in 2013, pre-harvest of the first forest rotation. Percentages of sand, silt, and clay, bulk density (B.D.), pH (1:1 soil/water by volume), CEC (Cation Exchange Capacity), C (Carbon), N (Nitrogen), P (Phosphorus), K (Potassium), Ca (Calcium), Mg (Magnesium), Fe (Iron)) expressed in kg ha^{-1}.

Soil Properties	Sand	Silt	Clay	B.D.	pH	CEC	C:N	C	N	P	K	Ca	Mg	Fe	Al
	(%)			(g cm-3)		(cmolc kg-1)		kg ha −1							
Alfisol	81.5	11.3	7.2	1.3	4.5	4.9	20.3	24,427	1205	19	27	241	28	284	1240
Spodosol	92.6	4.4	3	1.3	4.5	3.5	28.6	16,551	578	15	9	42	9	92	582

increases, and foliar P were analyzed using one-way ANOVAs with P fertilization treatment as a fixed effect by each site and year. O horizon P content, concentration, and mass collected from the first rotation in 2013 were also analyzed using one-way ANOVAs with P fertilization treatment as the fixed effect separated by site using JMP ®, Version 16.0.0. SAS Institute Inc., Cary, NC, 1989–2021. Resin-P and M3P extractions were analyzed using a repeated-measures ANOVA, treating each burial period or sampling time-point as a level across P fertilization treatment means. Bed and interbed samples were treated as random effects within these models (Maxwell et al., 2017). This design treats time as an independent variable using an unconstructed variance-covariance matrix simultaneously with each treatment. Pairwise comparison tests were performed using Dunnett's post hoc multiple comparisons using a 0.10 alpha value. Each treatment was compared to the control (0 + 0 P) within each site using Dunnett's multiple comparisons. Error bars represent treatment standard error for all figures. Asterisks in parentheses for all statistical comparisons were (*) Weak p-value < 0.10 (**) Moderate p-value < 0.05 (***) Strong p-value < 0.01 (Muff et al., 2022). Simple linear regressions using 95% confidence intervals were performed, treating tree heights by year as the dependent variable for M3P, resin P, foliar P, and O horizon samples taken to determine which and when measurements should be taken for best overall predictors of plant growth. All analyses were conducted using GraphPad Prism 9.5.0.

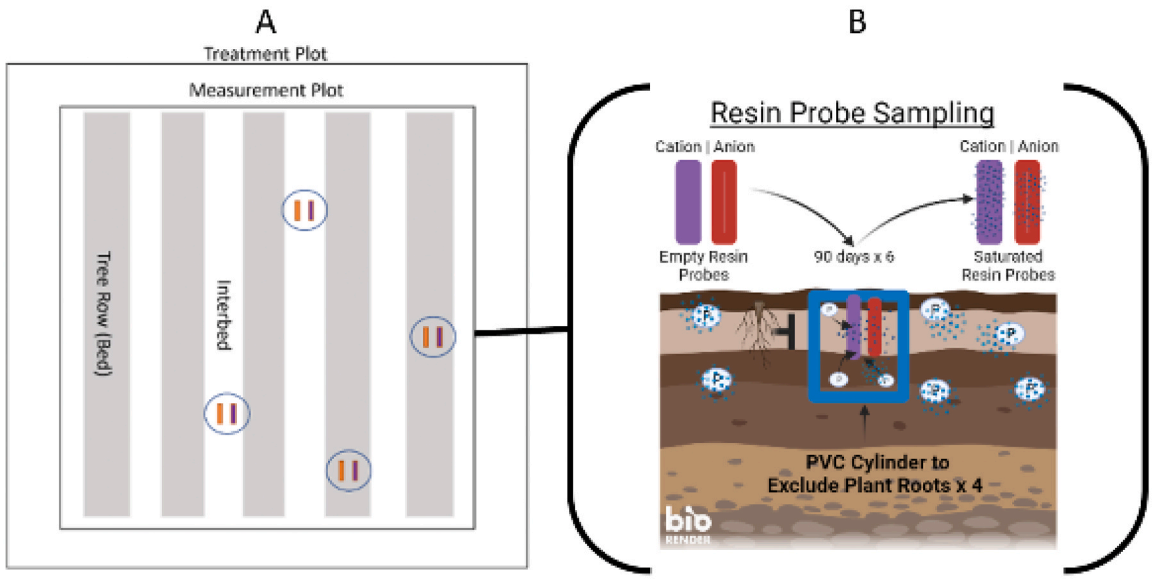

Fig. 2. Four pairs of resin probes were installed evenly between the bed and interbed for each treatment plot (A). Probes were excluded from the roots via a 25 cm diameter PVC pipe buried flush with the top soil down to 15. Probes were extracted after 90 days in the ground.

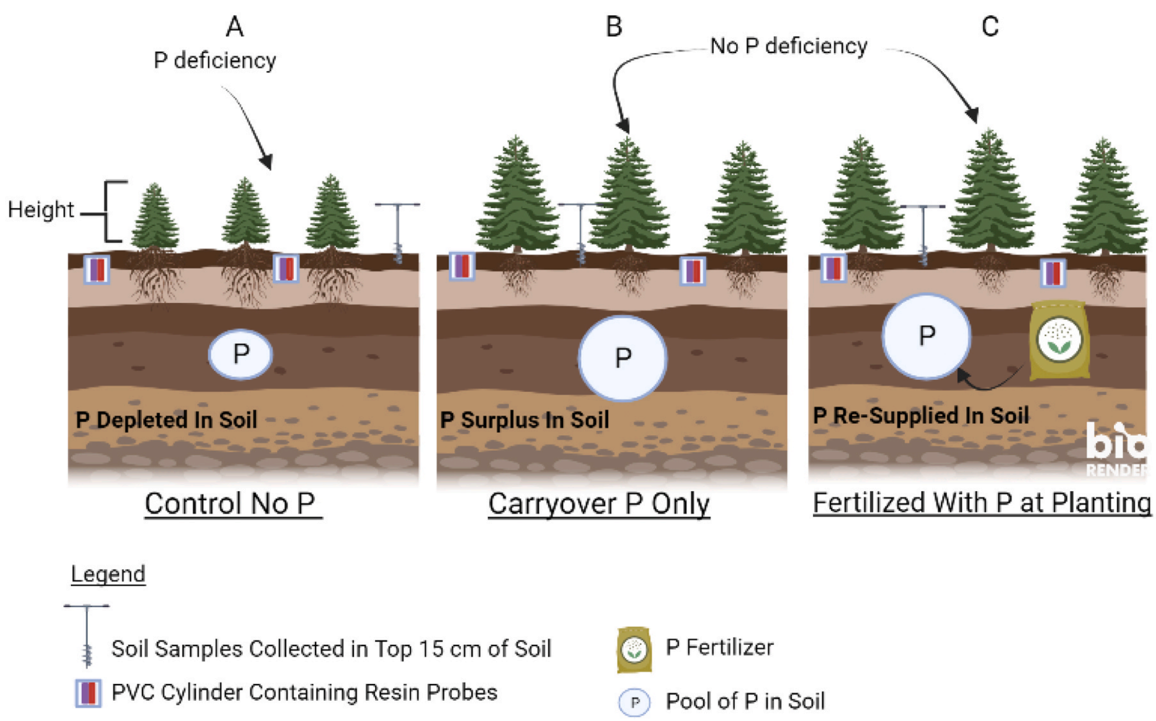

Fig. 3. Phosphorus carryover experimental design for fertilization and soil sampling in the top 0–15 cm of soil with a soil auger and resin probes collected passively over 3-month intervals.

3. Results

3.1. First rotation tree growth responses vs. second rotation tree growth responses

In the first rotation, before any fertilization was applied, there were no volume differences for the Spodosol (p-value = 0.79) at year three or the Alfisol (p-value = 0.49) at year five compared to the control plots (Fig. 4).

In the second rotation, by the end of the second year of growth, strong differences in height and height increment increases were observed among carryover and fertilization treatments for each site (Fig. 4). For the second rotation, in the Alfisol, there was very strong evidence that tree heights in the 81 + 0 P, the 121 + 0 P, and the 40 + 45 P treatments were significantly larger than the control by 13%, 15%, and 17%, respectively. There was substantial evidence for the Spodosol at age two that the 81 + 45 P and the carryover 60 + 0 P treatments increased height by 16% and 14%, respectively, compared to the control (Fig. 5).

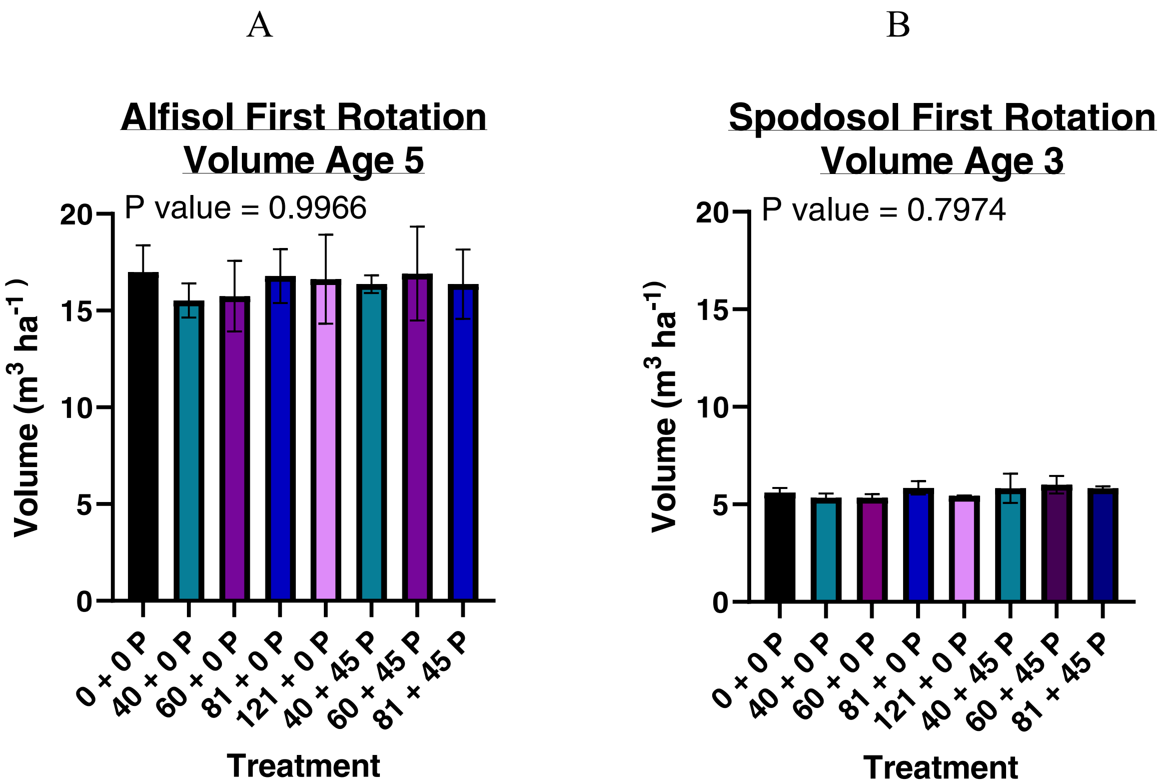

Fig. 4. First rotation data collected for the Alfisol (A) and the Spodosol (B) at ages 5 and 3, respectively. Volume data collected shows no significant differences among treatments for each site. Error bars represent standard error for individual treatment means.

3.2. Foliar P decreased in year two for each site

Needle concentration P decreased by 70% in the Alfisol and 150% in the Spodosol from year one to year two for carryover treatments (p-value < 0.01). The re-fertilized treatments only had 25–30% decreases in needle concentration P from year one to year two for the Alfisol (Fig. 6). In the Alfisol, re-fertilized (+ 45 P) treatments were higher in foliar P than the control treatment for year two. In the Spodosol, no differences between carryover treatments and re-fertilized treatments were detected.

3.3. Resin-P responses are highly dependent on site

In the Alfisol, resin-P was highest in the re-fertilized 40 + 45 P and the 121 + 0 P carryover treatments with 598% and 191% increases in resin P, respectively, from the 0 −90 and 90 −180-day burial periods (p-value = 0.03; Fig. 7). Carryover effects were only observed for the 121 + 0 P plots compared to the control (p-value ≤ 0.01). The 0 + 0 P treatment had no increases in resin-P in burial periods or sites from pre-harvest levels to the experiment's conclusion. Comparing sites, the Spodosol had almost one order of magnitude greater resin-P than the Alfisol (p-value ≤ 0.01). Resin-P increased in the Spodosol in all carryover treatments except the 121 + 0 P treatment until the 180–270 or 270–360-day burial periods. The 40 + 0 P and the 60 + 0 P Spodosol carryover treatments had significantly higher resin-P across burial periods than the control (p-value = 0.04). The re-fertilized treatment, 40 + 45 P, immediately increased resin-P, resulting in a 945% average increase in resin-P to fertilization in the 0–90 days post-planting, post-fertilization burial period—the fertilized treatment maintained higher levels of resin-P than pre-harvest levels for the remainder of the experiment.

3.4. Resin-P relationships to height were highly dependent on the burial period, site, and sampling location

For the Alfisol, it appeared that pre-harvest samples (−90 - 0 days) (p-value = 0.02; R^2: 0.49) and the post-planting (180 - 270 days) (p-value ≤ 0.01; R^2: 0.58) burial periods had the best overall relationship to tree height growth by year two. Only the pre-harvest resin-P samples collected for the Spodosol had a weak relationship to height at year two (p-value = 0.08; R^2: 0.37). Samples collected after harvest had little relationship to tree height (Supp. Table 1).

3.5. Mehlich 3 was highly sensitive to burial period and timing of sample collection

There was strong evidence that M3P extraction results were affected by the main effects of year and P fertilization treatment (p-value ≤ 0.01), but no interaction between the two effects. For the Alfisol, M3P concentrations were close to or above the ten ppm P threshold for *P. taeda* growth response (Wells et al., 1986) in most of the carryover and fertilized treatments but not in the control. ANOVA results indicated significant differences among P treatment means (p-value = 0.03) for year one, showing that 121 + 0 P carryover treatment had a 360% increase from the control treatment but not for any other treatment. Year two, which was one year post-fertilization, indicated that the re-fertilized 40 + 45 P and the carryover 121 + 0 P treatments were significantly higher than the control by 393% (p-value ≤ 0.01) and 437% (p-value = 0.014). By year 3, the 40 + 45 P and the 121 + 0 P treatments returned to year one levels in the top 15 cm of soil. No significant carryover effect was detected for the Spodosol treatment at year one (pre-fertilization). In year two, one year after fertilization, all treatments were significantly higher in M3P than the previous year (p-value = 0.02) but were not proportional to the amount of carryover or fertilized P applied. By year 3, three years post-planting and fertilization, all treatments were significantly higher in M3P than year one

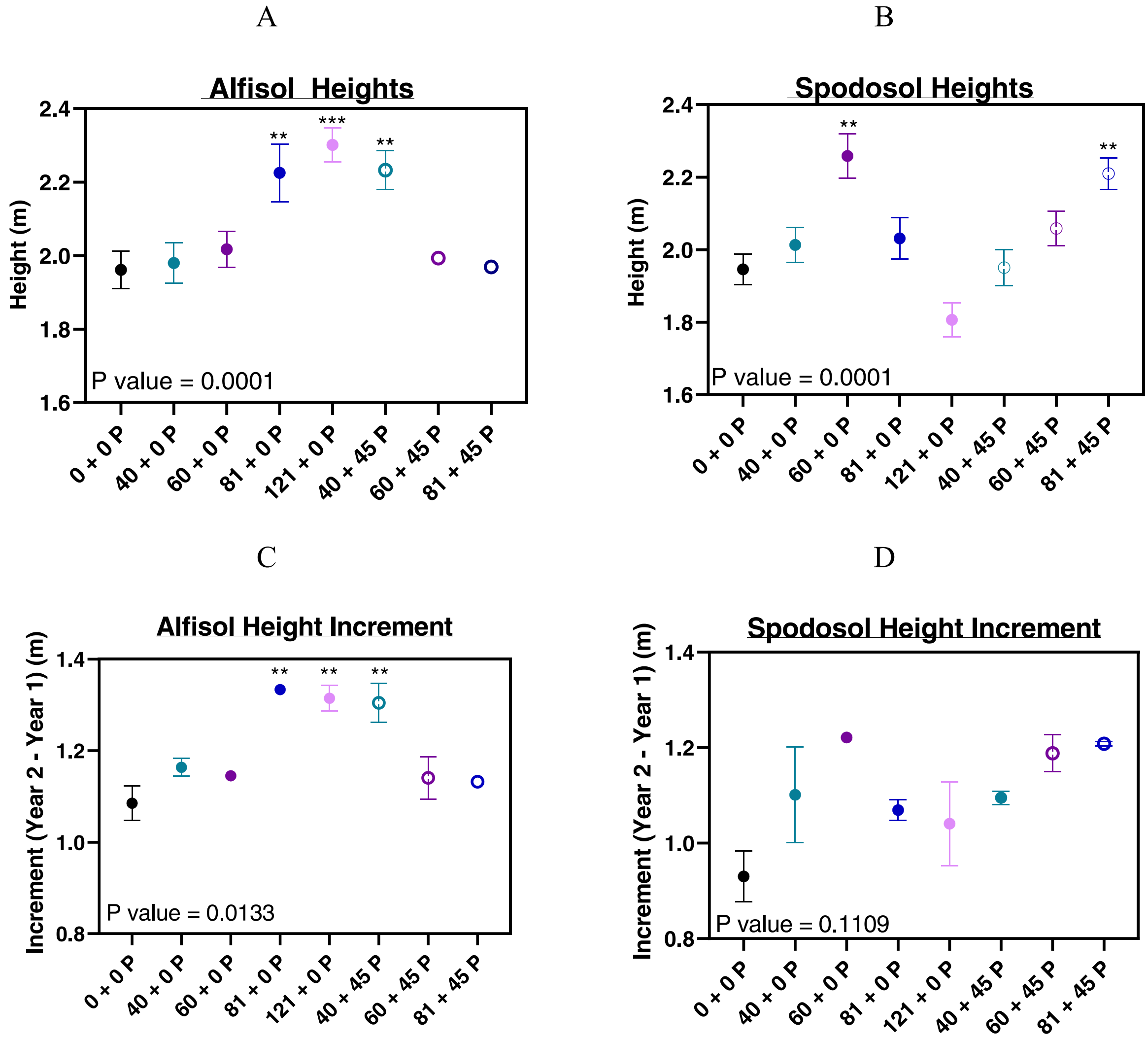

Fig. 5. Second rotation 2-year-old heights and height growth increments by P fertilization treatment effects for the Alfisol and Spodosol. Re-fertilized treatments with an additional 45 kg P ha^{-1} maintained larger heights (A) and growth (C) for the Alfisol. The Spodosol only had increases in height (B) but not growth for the 81 + 45 kg P ha^{-1} treatment (D). P values within each figure refer to model interaction. Each treatment was compared to the control (0 + 0 P) within each site using Dunnett's multiple comparisons (*). Error bars represent treatment standard error. Asterisk's statistically significant differences from the control are (*) weak p-value < 0.10, (**) moderate p-value < 0.05 (***), and strong p-value < 0.01 (Muff et al., 2022).

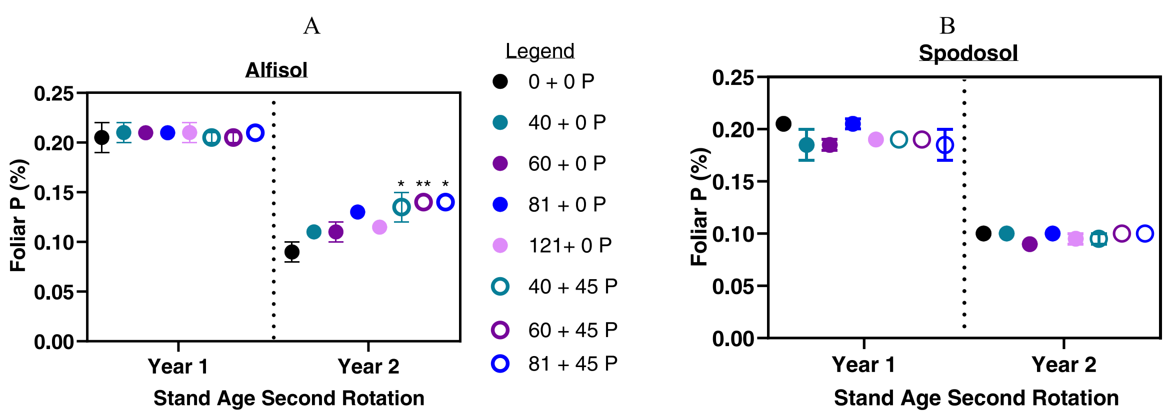

Fig. 6. Foliar P concentration change from year one to year two for the Alfisol (A) and the Spodosol (B). Asterisks (*) indicate differences between year two foliar P concentrations of each treatment from the control. Error bars represent the standard error of the treatment mean. (*) Weak p-value < 0.10 (**) Moderate p-value < 0.05 (***) Strong p-value < 0.01. (Muff et al., 2022).

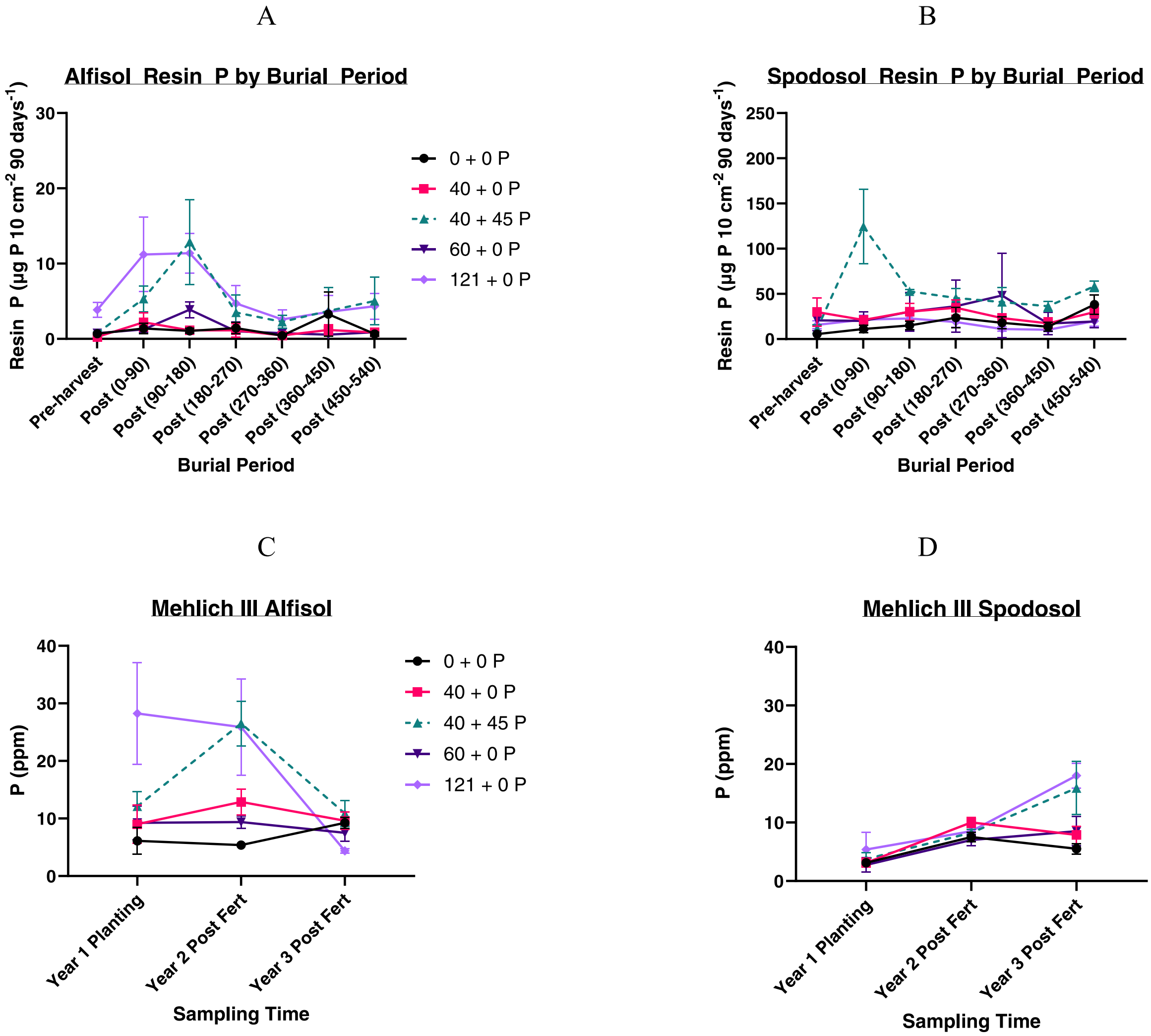

Fig. 7. Resin-P (μg P per 10 cm^2 of resin over 90 days) changes over seven burial periods (total of 600 days) for Alfisol (A) and Spodosol (B) collected in the top 15 cm of soil. Each line and color represents a different treatment over all the burial periods. Mehlich 3 Phosphorus (M3P) results in the top 15 cm of soil depth collected from the bed rows for Alfisol (C) and Spodosol (D) over the first three years from the establishment of the stand. The carryover treatments and re-fertilized treatments for each plot are represented as solid lines and a dotted line per graph, respectively. Error bars represent one standard error of the mean for each sampling point and P fertilization treatment.

pre-fertilization levels (p-value $\leq$ 0.01). Only the 121 + 0 P treatment was higher (p-value = 0.05) in year three than in the previous year (Fig. 7). In the Spodosol, only the 121 + 0 P and 40 + 45 P treatments were above the 10 ppm P threshold by the third year of sampling.

3.6. Mehlich 3 relationships to tree height and growth were site, timing, and location-dependent

The relationships between tree growth and production varied depending on the location of the sample within the plot, the year of measurement, and the site. In the case of the Alfisol, tree heights exhibited a stronger relationship with samples collected from the bed (p-value = 0.03; R^2: 0.46), while there was no significant relationship with samples taken from the interbed (p-value = 0.84; R^2: = 0.016). Specifically, the height of two-year-old trees in the Alfisol positively correlated with the quantity of M3P obtained from each soil sample collected in the second year. On the other hand, for the Spodosol, the relationships between tree growth and soil samples varied significantly depending on the measurement year and sampling timing (Supp. Table 1, Fig. 8).

3.7. O Horizon P content provided strong relationships to tree heights between sites

In the first rotation, the Spodosol accumulated more O horizon mass and P content than the Alfisol for almost all treatments (p-value = 0.04). This relationship was strongly related to the amount of P applied during the first 12 years of growth for both sites, with increasing rates of P strongly related to increasing P fertilization amendments (Supp. Fig. 1; p-value $\leq$ 0.01). The relationship between the O horizon P content from the previous rotation and the growth of the second rotation was examined for year one and year two at each site (Supp. Table 2). The results showed that the P content, P concentration, and forest floor mass from the first rotation were moderately to strongly correlated with the height outcomes of the Spodosol in the first year of growth. However, these variables did not show a significant relationship with the height results in the second year of growth. In the case of the Alfisol, the O-horizon P content exhibited a moderate association with the growth outcomes in the first year and a strong correlation with the growth results in the second year (Fig. 8).

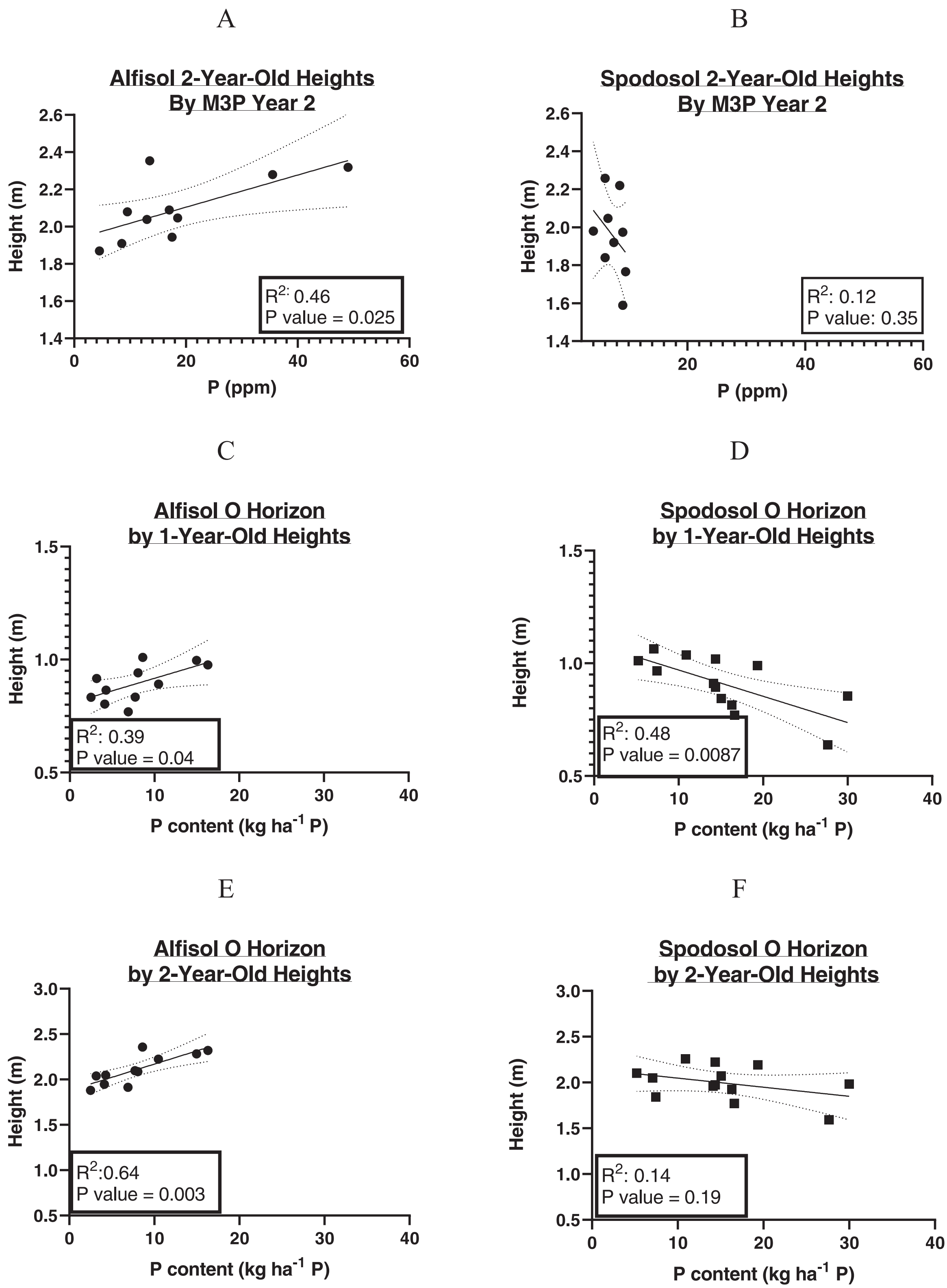

Fig. 8. Linear regressions with 95% confidence intervals (dotted lines) for Mehlich 3 Phosphorus (A, B) and O horizon samples (C-F) collected for the Alfisol (A) and Spodosol (B). First rotation O horizon P content relationships to average plot-level tree height for the second rotation's first and second year of growth. (C): Alfisol year one height, (D): Spodosol year one height, (E): Alfisol year two heights, (F): Spodosol year two heights.

4. Discussion

The first rotation sites were established in 1998 and 1999 for the Spodosol (Age 3) and the Alfisol (Age 5), respectively. Volume measurements were taken from each treatment plot before introducing any fertilization treatments, revealing a relatively uniform volume distribution for each site's respective age. As the second rotation commenced, notable differences in tree productivity and soil P concentrations emerged across treatments in the second year of growth. This suggests carryover effects from the first rotation and evidence that fertilized P is still available in the site even after 20 years (Comerford et al., 2002; Crous, 2007; Everett and Palm-Leis, 2009). Our findings suggest that applied P for the Spodosol and the Alfisol directly influenced tree height in the subsequent rotation, compared to control plots that received no P in either the first or second rotation. Results for the Spodosol were highly variable, and although we cannot provide reliable suggestions for the minimum P amounts required to enhance overall growth, our height results demonstrate that additional fertilization with P and carryover rates on these sites improves productivity compared to the control groups that received no P fertilization.

The duration of nutrient release from the decomposition of organic material, as shown by foliar P and soil P, is highly dependent on site and soil characteristics (Kiser and Fox, 2012). Peak foliar P concentrations for each site occurred during the first year of growth, with all treatments and sites almost double the 0.10% critical threshold (Wells et al., 1986). By the second year, all plots and treatments dropped in foliar P concentration significantly, with many treatments at or just above the 0.10% critical threshold for each site. We attribute this higher rate of P uptake in the needles by the trees during year one to increased metabolic rates resulting from large amounts of available nutrients to temporarily increase the photosynthetic capacity of the saplings to build leaf area (Gough et al., 2004; Kiser and Fox, 2012). We found that the P content of O horizon in the first rotation was negatively associated with increases in foliar P collected during year one of the second rotation for the Spodosol but positively associated with the Alfisol. The negative relationship implies that the P in the organic material and leaf litter has not yet been released into the soil by microbial processes in the Spodosol but has been in the Alfisol. Subedi et al. (2021) alluded that microbial respiration in Spodosols is suppressed in sites previously fertilized with N and P but accelerated in sites that have not received fertilization before. We can conclude from this that many of the Spodosol treatments are likely not P deficient and break down organic material at a slower rate than the Alfisol, which has significantly less organic material than the Spodosol from our results. Interestingly, the response to fertilization was not reflected in Spodosol foliar P for any of the carryover or re-fertilized treatments. However, the same treatments are highly variable in height, implying that foliar P might not be the best metric for testing for P deficiencies in these sites at this stage of development.

These resins appeared to capture the magnitude and extent of the initial pulse of nutrients from harvest and site preparation for each treatment as the excess organic material was mineralized into the inorganic P pool in the top 15 cm of soil (Comerford and De Barros, 2005). Resin-P results were variable between sites, with the Spodosol adsorbing 100% more resin-P over each burial period than the Alfisol for some treatments. Interestingly, this dramatic increase in resin-P was not represented in M3P extractions for the Spodosol, where many of the extractions were well below the Alfisols values across the whole experiment. This alludes to how the resins interact with the soil and P held within it. The M3P extraction results indicate that there is almost 100% more Fe and Al in the top 0–15 cm of soil in the Alfisol than the Spodosol, dramatically increasing the amount of sites P could be adsorbed to (Pierzynski et al., 2005). Also, considering that the Spodosol is significantly sandier than the Alfisol, we propose that P is significantly more mobile in the Spodosol than the Alfisol. This result is further evidenced by the re-fertilized plots, which show the magnitude of fertilization response was site dependent, with the fertilization causing the Spodosol to increase by 990% and 142% for the Alfisol. In the following burial period after each peak, the Spodosol decreased by 52%, while the Alfisol decreased by almost 267% from the peak, even though the same amount of fertilizer was applied at each site (Condron et al., 2005; Kiser and Fox, 2012). The peaks of these increases occurred during the 0–90 day burial period for the Spodosol and 90–180 day burial period for the Alfisol, indicating that the sequestration and mobility of fertilizer P is occurring at very different rates in the Alfisol than the Spodosol. Additionally, these results also explain why there was a negative relationship between O horizon P content and mass with the Spodosol but a positive relationship with the Alfisol. This result once again indicates that the Alfisol was cycling the organic material at a faster rate than the Spodosol, which had a negative relationship with increasing O horizon P content, supported by Subedi et al. (2021) and that the organic material P content and mass were directly related for the increases in soil respiration and mineralization for the Alfisol, but had a suppressive effect for the Spodosol which was already not P deficient.

5. Conclusion

Our study aimed to determine the duration of the P carryover effect and the magnitude of response to soil P as it relates to previously applied P fertilizer rates from the previous rotation. With the rising costs of P fertilizer, improved management of P nutrition is a requirement for landowners and growers. Determining if and for how long fertilized P remains in the forest system and if that soil P can be carried over into subsequent rotations would save growers on up-front fertilization costs and P testing. For Alfisols, our results indicate that re-fertilization with 45 kg P ha^{-1} at planting is recommended when soil M3P concentration levels fall below 20 ppm (as measured at planting from the bed) or when resin probe data indicates less than ten μg P 10 cm^{-2} over a 90-day burial period within the first 180 days post-planting. The relationship between increasing P rates and height growth responses for two-year-old *P. taeda* was not consistently proportional to the magnitude of applied P. In the case of the Alfisol, our data indicated that application of P exceeding 81 kg P ha^{-1} from either the first or second rotation results in a 13% to 17% increase in total height responses. Treatments with less than 81 kg P ha^{-1} did not show growth responses compared to the controls. Heights for the Spodosol and the Alfisol were related to O horizon P content from the previous rotations litter layer. These findings strongly suggest that sampling from the O horizon before the harvest of a mature stand may provide better fertilization recommendations than sampling from the mineral soil. Our results also revealed some exciting site-specific carryover and fertilization effects for P that will be invaluable in determining whether a site is P-deficient. It appears that for the Spodosol, the top 0–15 cm of soil is not the best place to sample when using soil extraction techniques, and perhaps deeper subsurface horizons should be targeted for better growth prediction results. The top 0–15 cm on the Alfisol, on the other hand, appears to be a massive sink for P, and until enough P is added, it will continue to adsorb that P onto various metal and soil complexes. Overall, our results demonstrate that a one-size-fits-sample-all solution is not going to come about anytime soon in production silviculture and that a site-specific approach is necessary to understand the limitations and requirements of a stand as to whether it will be P deficient based on previous fertilization history, soil type, and environmental conditions.

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Declaration of Generative AI and AI-assisted technologies in the writing process

While preparing this work, the author used Grammarly A.I. Writing Assistance to improve the readability and grammar of the document. Generative A.I. was not used to generate unique results, references, or text in any capacity. After using this tool/service, all content was reviewed by the author, edited as needed, and takes full responsibility for the publication's content.

CRediT authorship contribution statement

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Declaration of Competing Interest

No competing interests to declare.

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.121701.

References

Albaugh, J.M., Blevins, L., Allen, H.L., Albaugh, T.J., Fox, T.R., Stape, J.L., Rubilar, R.A., 2010. Characterization of foliar macro-and micronutrient concentrations and ratios in loblolly pine plantations in the southeastern United States. South. J. Appl. For. 34 (2), 53–64.

Albaugh, T.J., Fox, T.R., Cook, R.L., Raymond, J.E., Rubilar, R.A., Campoe, O.C., 2019. Forest fertilizer applications in the southeastern United States from 1969 to 2016. For. Sci. 65 (3), 355–362.

Amateis, R.L., Burkhart, H.E., Allen, H.L., & Montes, C., 2001. "Fertilized and thinned loblolly pine plantations." (FMRC, Virginia Tech).

Ballard, R., 1978. Effect of first rotation P applications on fertilizer requirements of second rotation Radiata pine. NZJ For. Sci. 8 (2), 135–145.

Ballard, R., 1980. Phosphorus nutrition and fertilization of forest trees. In: Khasawneh, F. E., Sample, E.C., Kamprath, E.J. (Eds.), The Role of Phosphorus in Agriculture. Am. Soc. Agron., Madison, WI, pp. 763–804.

Cade-Menun, B.J., Elkin, K.R., Liu, C.W., Bryant, R.B., Kleinman, P.J., Moore, P.A., 2018. Characterizing the P forms extracted from soil by the Mehlich III soil test. Geochem. Trans. 19 (1), 1–17.

Comerford, N.B., De Barros, N.F., 2005. P nutrition of forest trees. P Agric. Environ. 46, 541–558.

Comerford, N.B., McLeod, M., Skinner, M., 2002. P form and bioavailability in the pine rotation following fertilization: P fertilization influences P form and potential bioavailability to pine in the subsequent rotation. For. Ecol. Manag. 169 (3), 203–211.

Condron, L.M., Turner, B.L., Cade-Menun, B.J., 2005. Chemistry and dynamics of soil organic P. P Agric. Environ. 46, 87–121.

Crous, J.W., Morris, A.R., Scholes, M.C., 2007. The significance of residual P and potassium fertilizer in countering yield decline in a fourth rotation of *Pinus patula* in Swaziland. South. Hemisph. For. J. 69 (1), 1–8.

Doydora, S., Gatiboni, L., Grieger, K., Hesterberg, D., Jones, J.L., McLamore, E.S., Duckworth, O.W., 2020. Accessing legacy P in soils. Soil Syst. 4 (4), 74.

Everett, C.J., Palm-Leis, H., 2009. Availability of residual P fertilizer for loblolly pine. For. Ecol. Manag. 258 (10), 2207–2213.

Fisher, R.F., Garbett, W.S., 1980. Response of semimature slash and loblolly pine plantations to fertilization with nitrogen and P. Soil Sci. Soc. Am. J. 44 (4), 850–854.

Fox, T.R., Comerford, N.B., 1990. Low-molecular-weight organic acids in selected forest soils of the southeastern USA. Soil Sci. Soc. Am. J. 54 (4), 1139–1144.

Fox, T.R., Miller, B.W., Rubilar, R., Stape, J.L., Albaugh, T.J., 2011. P nutrition of forest plantations: the role of inorganic and organic P. P Action. Biol. Process. Soil P Cycl. 317–338.

Gent, J.A., Allen, H.L., Campbell, R.G., Wells, C.G., 1986. Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and P fertilization. South. J. Appl. For. 10 (3), 124–128.

Gough, C.M., Seiler, J.R., 2004. Belowground carbon dynamics in loblolly pine (Pinus taeda) immediately following diammonium phosphate fertilization. Tree Physiol. 24 (7), 845–851.

Hansen, T.H., De Bang, T.C., Laursen, K.H., Pedas, P., Husted, S., Schjoerring, J.K., 2013. Multielement plant tissue analysis using ICP spectrometry. Plant Miner. Nutr. Methods Protoc. 121–141.

Harris, W.G., Chrysostome, M., Obreza, T.A., Nair, V.D., 2010. Soil properties pertinent to horticulture in Florida. HortTechnology 20 (1), 10–18.

Karamanos, R.E., Robertson, J.A., Puurveen, D., Domier, K.W., 2013. Assessment of P status in a long-term tillage and P placement experiment. Commun. Soil Sci. Plant Anal. 44 (1-4), 219–231.

Kiser, L.C., Fox, T.R., 2012. Soil accumulation of nitrogen and P following annual fertilization of loblolly pine and sweetgum on sandy sites. Soil Sci. Soc. Am. J. 76 (6), 2278–2288.

Maxwell, S.E., Delaney, H.D., & Kelley, K., 2017. Designing experiments and analyzing data: A model comparison perspective Routledge.

Meason, D.F., Idol, T.W., Friday, J.B., Scowcroft, P.G., 2009. Effects of fertilization on P pools in the volcanic soil of a managed tropical forest. For. Ecol. Manag. 258 (10), 2199–2206.

Mehlich, A., 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15 (12), 1409–1416.

Muff, S., Nilsen, E.B., O'Hara, R.B., Nater, C.R., 2022. Rewriting results sections in the language of evidence. Trends Ecol. Evol. 37 (3), 203–210.

Pierzynski, G.M., McDowell, R.W., Thomas Sims, J., 2005. Chemistry, cycling, and potential movement of inorganic phosphorus in soils. Phosphorus. Agric. Environ. 46, 51–86.

Plassard, C., Louche, J., Ali, M.A., Duchemin, M., Legname, E., Cloutier-Hurteau, B., 2011. Diversity in phosphorus mobilisation and uptake in ectomycorrhizal fungi. Ann. For. Sci. 68 (1), 33–43.

Pritchett, W.L., 1968. Progress in the development of techniques and standards for soil and foliar diagnosis of phosphorus deficiency in slash pine. For. Fertili. Theory Pract. Tenn. Val. Auth. 81–87.

Pritchett, W.L., Comerford, N.B., 1982. Long-term response to P fertilization on selected southeastern coastal plain soils. Soil Sci. Soc. Am. J. 46 (3), 640–644.

Pritchett, W.L., Llewellyn, W.R., 1966. Response of slash pine (P*inus elliottii engelm. Var. elliottii*) to P in sandy soils. Soil Sci. Soc. Am. J. 30 (4), 509–512.

Pritchett, W.L., Swinford, K.R., 1961. Response of slash pine to colloidal phosphate fertilization. Soil Sci. Soc. Am. J. 25 (5), 397–400.

Qian, P., Schoenau, J.J., 1995. Assessing nitrogen mineralization from soil organic matter using anion exchange membranes. Fert. Res. 40, 143–148.

Qian, P., Schoenau, J.J., 2002. Practical applications of ion exchange resins in agricultural and environmental soil research. Can. J. Soil Sci. 82 (1), 9–21.

Schoenau, J.J., Qian, P., & Huang, W.Z.,1993. Ion-exchange resin strips as plant root simulators. Paper presented at the *Soils and Crops Workshop*.

Subedi, P., Jokela, E.J., Vogel, J.G., Bracho, R., Inglett, K.S., 2021. The effects of nutrient limitations on microbial respiration and organic matter decomposition in a Florida Spodosol as influenced by historical forest management practices. For. Ecol. Manag. 479, 118592.

Tacilla Villanueva, A., 2015. *Impacts of fertilization on soil properties in loblolly pine plantations in the southeastern United States* (Masters thesis, Virginia Tech).

Tejowulan, R.S., Schoenau, J.J., & Bettany, J.R. , 1994. Use of ion-exchange resins in soil and plant testing for micronutrient availability. Paper presented at the *Soils and Crops Workshop*.

Tiessen, H., Abekoe, M.K., Salcedo, I.H., Owusu-Bennoah, E., 1993. Reversibility of P sorption by ferruginous nodules. Plant Soil 153, 113–124.

Turner, J., Lambert, M.J., 1986. Effects of forest harvesting nutrient removals on soil nutrient reserves. Oecologia 70 (1), 140–148.

Turner, J., Lambert, M.J., 2002. Litterfall and forest floor dynamics in *Eucalyptus pilularis* forests. Austral Ecol. 27 (2), 192–199.

Van Raij, B., Quaggio, J.A., Da Silva, N.M., 1986. Extraction of P, potassium, calcium, and magnesium from soils by an ion-exchange procedure. Commun. Soil Sci. Plant Anal. 17 (5), 547–566.

Vitousek, P.M., Porder, S., Houlton, B.Z., Chadwick, O.A., 2010. Terrestrial P limitation: mechanisms, implications, and nitrogen–P interactions. Ecol. Appl. 20 (1), 5–15.

Walker, T.W., Syers, J.K., 1976. The fate of P during pedogenesis. Geoderma 15 (1), 1–19.

Wells, C.G. , 1973. Soil and foliar guidelines for phosphorus fertilization of loblolly pine (Vol. 110). U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Wells, C.G., Craig, J.R., Kane, M.B., Allen, H.L., 1986. Foliar and soil tests for the prediction of P response in loblolly pine. Soil Sci. Soc. Am. J. 50 (5), 1330–1335.