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ARTICLE

Soil Tillage, Conservation, & Management

Cover cropping increased phosphorus stocks in surface sandy Ultisols under long-term conservation and conventional tillage

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Abstract

Low use-efficiency and high environmental significance of phosphorus (P) requires a better understanding of its stocks and behavior in soils. We investigated P fractions in sandy Coastal Plain Ultisols, where long-term conservation agriculture driven by conservation tillage and residue return for ∼40 yr and the integration of cover cropping for 4 yr has been demonstrated to improve soil organic matter. Soils were collected from fields at 0- to 5- and 5- to 15-cm depths to study the effects of tillage (conservation vs. conventional) and cover crop (with vs. without) on soil stocks of various chemically defined P pools and the phosphatase potential activities. Conservation tillage increased KCl-extractable inorganic P (KCl-Pi) stocks in top soils (0–5 cm) when compared to conventional tillage, but had no effects on other pools at both soil depths. Cover cropping caused significant accumulations of NaOH-extractable organic P (NaOH-Po) in top soils (0–5 cm). Nonetheless, neither conservation tillage nor cover crop changed the contributions of the chemically defined pools to soil total P with NaOH-Po dominating at both soil depths followed by NaOH-extractable inorganic P (NaOH-Pi) and HCl-extractable Pi (HCl-Pi). Conservation tillage increased phosphatase potential activities by 128% in the 0- to 5-cm soils, whereas no cover crop effects were observed. Conservation tillage improved P availability potentially through its effects on microbial activities, whereas cover cropping increased P stocks and availability by promoting Po accumulations.

1 | INTRODUCTION

Phosphorus is an essential plant nutrient and therefore an important component of soil fertility in production agriculture. However, most soils are deficient in P in forms that are readily available to crops and thus require fertilization to ensure high levels of productivity (Roy et al., 2016; Shen et al., 2011). Nonetheless, the recovery of P from fertilizers by plants is often low in the year of application with a varying but substantial part either retained in soils in less available forms (Richardson, 2001; Syers, Johnston, & Curtin, 2008; Whalen & Chang, 2001) or exported by leaching and runoff, which has been commonly implicated to accelerate eutrophication in aquatic systems (Schindler, Carpenter, Chapra, Hecky, & Orihel, 2016). The low use-efficiency and high environmental significance of P highlights the needs for better understanding of P processes in agroecosystems (Dodd & Sharpley, 2016; Kleinman et al., 2015). In particular, the widespread use of conservation tillage and renewed interest on cover crops in

Abbreviations: CA, conservation agriculture; Pi, inorganic phosphorus; Po, organic phosphorus; SOC, soil organic carbon; TC, total carbon; TN, total nitrogen; TP, total phosphorus.

the southeastern Coastal Plain region call for improved understanding of the distribution, availability, and transformation of P under these two integrated soil management practices.

Soil P is present in many chemical forms, either as inorganic P (Pi) or organic (Po). These chemical forms can be operationally designated into different pools by sequential chemical extractions (Kuo, Huang, & Bembenek, 2005; Shen et al., 2011). Such extraction procedures assume that different extractants selectively extract discrete P chemical forms related to their degree of recalcitrance. Though the sequential procedures are operationally defined, the methods provide a convenient way to characterize the behavior and fates of the individual P pools in soils and to assess their effects on the environment (Margenot et al., 2017; Shen et al., 2011; Yan, Wei, Hong, Lu, & Wu, 2017; Ye, Wright, McCray, Reddy, & Young, 2010). Soils with high Pi in solution (KCl-extractable, readily available) indicate high P availability to plants but also high potentials for leaching and surface runoff. Inorganic P associated with calcium carbonate ($CaCO_3$; HCl-extractable, moderate available) and aluminum (Al) and iron (Fe) oxides (NaOH-extractable, moderate available) are considered relatively stable, but may be susceptible to dissolution and regeneration upon changes in soil conditions due to managements (crop rotation, liming, tillage, fertilization, etc.). In the case of P in organic pools (NaOH-extractable, unavailable), it may be unstable because of organic matter oxidation and P mineralization, which is partially controlled by the availability and activity of phosphatase enzymes produced by soil microorganisms and plant roots (Shen et al., 2011; Takeda, Nakamoto, Miyazawa, Murayama, & Okada, 2009).

All the designated P fractions exist in complex equilibria with each other, representing from very stable, moderate available to readily available P pools in soils (Shen et al., 2011; Ye et al., 2010). In production agriculture, additions of P-based fertilizers increased soil total P (TP) and changed its distribution in these pools, especially the one associated with Al and/or Fe oxides (Guardini et al., 2012, Yan et al., 2017). Similarly, soil amendment was found to increase Al and/or Fe bound and readily available P by reducing soil pH to release P from $CaCO_3$–bound fractions (Ye et al., 2010), while the implementation of conservation tillage promoted the accumulation of Po and increased phosphatase activity, but reduced plant available P (Wei, Chen, Zhang, Liang, & Chen, 2014). Other studies also demonstrated increases of Pi and Po under no-till (Zamuner, Picone, & Echeverria, 2008), but higher losses of dissolved P were also observed (Djodjic, Bergström, & Ulén, 2002; King et al., 2015). Additionally, organic amendment and cover crops enhanced phosphatase activity and microbial P encouraging P mineralization to improve its availability (Takeda et al., 2009). Clearly, soil management can alter the distribution and allocation of P in various pools by disrupting their equilibria.

Historical cultivation and management of the Coastal Plain soils of the southeastern United States resulted in extensive degradation of soil health—exacerbated by declining soil organic carbon (SOC) and destruction of soil structure—which impairs crop productivity and agroecosystem sustainability (Causarano et al., 2008; Novak & Busscher, 2013). To counter these effects, conservation agriculture (CA) was adopted with considerable promise to restore SOC and improve soil health (Palm, Blanco-Canqui, DeClerck, Gatere, & Grace, 2014). Minimal soil disturbance (e.g., conservation tillage) and continual soil cover (e.g., residue return and cover crop) are two key concepts of CA, both of which have frequently demonstrated to improve soil structure (Islam & Weil, 2000; Singh et al., 2016), SOC (Lal, 2015; Novak, Frederick, Bauer, & Watts, 2009), and crop yields (Giller et al., 2015; Schomberg et al., 2006) in many soils. Nonetheless, the P fractions, fixation, and transformation in these soils are less known.

The highly weathered character and low P sorption capacity of the surface horizons of Coastal Plain soils makes soil P vulnerable for leaching and run off losses and an environmental concern (Kleinman et al., 2007; Novak & Watts, 2004). Meanwhile, high concentrations of Fe and/or Al oxides and low pH of the clay-enriched subsurface soils (resulted from clay mineral weathering and clay eluviation) both promote P fixation and limit P availability to plants (Harris, Rhue, Kidder, Brown, & Littell, 1996; Scott & Bliss, 2012). Objectives of the present study were therefore to evaluate the effects of CA on P stocks, distribution, and transformation in sandy Coastal Plain soils. Long-term research plots (~ 40 yr) designed to investigate the effects of conservation tillage on SOC dynamics were used for this study. We also examined the short-term (~4 yr) effects of integrating winter cover crops. Relevant studies have demonstrated significant increases in SOC in the top soils under conservation tillage (Nash et al., 2018; Novak et al., 2009). It was therefore hypothesized that both conservation tillage and cover cropping would (a) increase Po stocks and hence soil TP, (b) decrease P fixation while increasing the stocks of readily available Pi, and (c) enhance phosphatase activity and P mineralization.

2 | MATERIALS AND METHODS

2.1 | Site description

The experiment was conducted at the Pee Dee Research & Education Center of Clemson University, Florence, SC (34°18′ N, 79°44′ W). Average annual precipitation was 1186 mm and the average annual high and low air temperature were 23.8 and 11.1 °C, respectively (US Climate Data, available online at https://www.usclimatedata.com/). The experimental site was established in 1979 to investigate the

TABLE 1 Phosphorus fertilization (kg ha^{-1}) history of the research sites (from 2000 to 2018)

Year	2000	2001	2002	2003	2006	2008	2009	2010	2018
Phosphorus	67	22	20	20	57	57	44	99	27

TABLE 2 Selected soil properties in a Norfolk soil under conservation agriculture. Values are means with one standard error. Different letters indicate significant difference at α = .05

	pH	Bulk density	Clay	Silt	MWD[a]	Total C	Total N	$NaHCO_3$-Pi	$NaHCO_3$-Po
		g cm^{-3}	———%———		mm	———g kg^{-1}———		mg kg^{-1}	
0 to 5-cm depth									
CS-Fallow	5.7 ± 0.1	1.30 ± 0.09	7.3 ± 0.3	13.3 ± 2.5	0.71 ± 0.17	13.2 ± 1.8ab	1.2 ± 0.1a	17 ± 3	53 ± 9
CS-Cover	5.7 ± 0.1	1.37 ± 0.03	7.3 ± 0.3	13.2 ± 1.6	0.71 ± 0.14	13.9 ± 1.6a	1.2 ± 0.1a	18 ± 1	58 ± 6
CV-Fallow	5.6 ± 0.1	1.43 ± 0.01	7.8 ± 0.2	13.3 ± 1.0	0.62 ± 0.10	10.0 ± 0.7b	0.8 ± 0.0b	14 ± 2	43 ± 6
CV-Cover	5.8 ± 0.1	1.33 ± 0.05	8.0 ± 0.3	13.2 ± 1.5	0.77 ± 0.05	10.2 ± 0.9b	0.9 ± 0.0 b	14 ± 4	46 ± 11
5- to 15-cm depth									
CS-Fallow	5.9 ± 0.1	1.51 ± 0.04	7.0 ± 0.4	13.7 ± 3.2	0.62 ± 0.07	7.3 ± 0.06	0.62 ± 0.00	15 ± 3	27 ± 4
CS-Cover	5.9 ± 0.2	1.48 ± 0.09	7.2 ± 0.3	14.6 ± 3.6	0.59 ± 0.06	9.5 ± 0.11	0.79 ± 0.01	15 ± 2	27 ± 3
CV-Fallow	5.8 ± 0.1	1.41 ± 0.04	7.7 ± 0.5	16.1 ± 2.0	0.60 ± 0.02	8.3 ± 0.12	0.68 ± 0.01	13 ± 4	25 ± 5
CV-Cover	5.8 ± 0.1	1.52 ± 0.05	8.1 ± 0.5	15.2 ± 2.8	0.64 ± 0.05	8.0 ± 0.12	0.62 ± 0.0	13 ± 5	26 ± 8

[a]MWD, mean weight diameter; Pi, inorganic P; Po, organic P; CS, conservation tillage; CV, convention tillage; Fallow, without winter cover crops; Cover, with winter cover crops.

effects of tillage (conventional vs. conservation) and residue management practices on a typical southeastern Coastal Plain soil (Hunt, Bauer, & Matheny, 1997). The soil was a Norfolk loamy sands (Fine- loamy, siliceous, thermic Typic Kandiudults). The study consists of five replicates each of conventional and conservation tillage plots. The plots have been consistently maintained since the establishment of the experimental site. Within each set of plots, the same crop rotation has been grown for each tillage system with all crop residues returned after harvest (Bauer, Frederick, Novak, & Hunt, 2006). Conventional tillage included disking (10–15 cm) two or three times annually with a one-pass subsoiling (30 or 42 cm) prior to planting the spring crops, while conservation tillage consisted of one-pass, in-row subsoiling only. Corn (*Zea mays*) was the sole crop during the first years. Crop rotation either with cotton (*Gossypium* L.) or soybean (*Glycine max*) was adopted in the mid-1980s. Winter cover crop mixtures (i.e., cereal rye [*Secale* L.] and crimson clover [*Trifolium incarnatum* L.]) were introduced to the experiment in 2015 as a split-plot in winter fallow plots. Additional site description, crop rotation, and management practice details can be found in relevant studies (Hunt et al., 1997; Karlen, Hunt, & Campbell, 1984; Nash et al., 2018; Novak, Bauer, & Hunt, 2007). The current experiment consisted of the following four treatments: (a) conservation tillage with cover crops (CS-Cover); (b) conservation tillage without cover crops (CS-Fallow); (c) conventional tillage with cover crops (CV-Cover); and (d) conventional tillage without cover crops (CV-Fallow). No manure or P fertilizers have been applied in any forms during the winter either with or without cover crops. However, during the cash crop season, monoammonium phosphate or diammonium phosphate was applied according to the recommendations provided by the Agricultural Service Laboratory of Clemson University on soil testing results (Table 1). Selected soil physio-chemical properties are presented in Table 2.

2.2 | Soil sampling

Before the end of the cover crops in 2018, 8–10 soil cores (2.5-cm diameter) were randomly collected from the first four replicate plots (16 plots in total) at 0- to 15-cm depth (i.e., the tillage layer) and sectioned into two increments (0–5 and 5–15 cm), because previous studies in these research plots demonstrated that significant SOC accumulations only occurred at the 0- to 5-cm depth, not in whole soils (Nash et al., 2018; Novak et al., 2007, 2009), while similar studies on P dynamics suggested that fertilizer P did not accumulate in low soil profiles (Scott & Bliss, 2012). Soils of the same depth from each plot were composited and transported to the laboratory, where they were sieved (2 mm) after the removal of plant materials and stored at 4 °C until used within a week. Soil samples for bulk density analysis were collected simultaneously.

2.3 | Soil analyses

Soil bulk densities were estimated after collection of samples with a 5-cm diameter AMS soil core sampler (AMS, American Falls, ID) and drying the soils at 60 °C for 3 d. Soil pH was measured with an Orion 8107 pH probe (Thermo scientific, Waltham, MA) in deionized water (1:3 w/w) after being equilibrated for 30 min. Soil particle-size distribution was estimated with the micro-pipette method (Miller & Miller, 1987). The stability of macro- (250–2,000 μm) and microaggregates (53–250 μm) was analyzed by wet sieving (Márquez, Garcia, Cambardella, Schultz, & Isenhart, 2004; Six et al., 2000). Sand contents (>53 μm) of each aggregate fraction were corrected according to (Six et al., 2000). Mean weight diameter was calculated as described by Márquez et al. (2004). Total C (TC) and N (TN) were determined using oven-dried (60 °C) and ground soils with a Carlo-Erba NA 1500 CNS analyzer (Haak-Buchler Instruments, Saddlebrook, NJ).

Soil P fractionation was performed with a sequential chemical extraction procedure (Yan et al., 2017; Ye et al., 2010). Approximately 1 g (dry equivalence) of soil was extracted with 25 ml of 1.0 M KCl for 1 h, passed through 0.45-μm membrane filters, and analyzed for P (KCl-Pi, readily available to plants). The remaining samples were extracted with 25 ml of 0.1 M NaOH for 17 h, filtered and analyzed for P (NaOH-Pi, moderate available to plants), followed by the extraction of remaining samples with 25 ml of 0.5 N HCl for 24 h and analysis of P (HCl-Pi, moderate available to plants). The remaining samples were further digested with 6 N HCl for 1 h at 150 °C and analyzed for residual P (Residual-P, unavailable to plants). A 3-ml sample of the NaOH extracts was digested with 11 N H_2SO_4 for 4 h at 350 °C and analyzed for total P (NaOH-TP). The organic P fraction (NaOH-Po, unavailable to plants) was calculated by the subtraction of NaOH-Pi from NaOH-TP. Phosphorous concentrations of extracts were measured using the molybdate blue-ascorbic acid method (Murphy & Riley, 1962).

Microbial biomass was measured by the fumigation-extraction method (Vance, Brookes, & Jenkinson, 1987). Both fumigated and unfumigated soil samples were extracted with 0.5 M NaHCO3 (pH 8.5) and the extracts were digested with 5.5 M H_2SO_4 for 4 h at 350 °C and analyzed for TP. Microbial biomass P (MBP) was determined as the difference in TP of $NaHCO_3$ extracts between fumigated and unfumigated soil. The $NaHCO_3$–Pi is the TP in undigested unfumigated extracts, while $NaHCO_3$–Po is the difference between the TP of the digested unfumigated extracts and the $NaHCO_3$–Pi.

Phosphatase potential activity was measured using fluorescence spectroscopy (Ye, Parajuli, & Sigua, 2019). Soil samples were mixed with 30 ml DI water and shaken for 20 min, followed by diluted five times for the assays. In a 96-well microplate, approximately 200-μl samples were incubated with 50 μl of respective substrates at room temperature (20 ± 1 °C) for 24 h, and was conducted in triplicates with controls to assess nonenzymatic production. Enzymatic activity was determined by calculating the mean fluorescence reading change over time with a standard curve and expressed as specific activities by dividing the apparent activities with MBP.

2.4 | Statistical analyses

A 2-way analysis of variance (ANOVA) of the main effects (i.e., tillage and cover crop) and their interactions were tested with the generalized linear model with a contrast function to exam the difference between individual treatments. Data were tested for normality and log-transformed if the transform substantially improved the overall distribution. Correlation analysis was conducted to determine relationships among measured variables. Significant level was set at $\alpha = .05$. All analyses were carried out with JMP Pro 14 (SAS Institute, Cary, NC).

3 | RESULTS

3.1 | P distributions in chemically defined pools

At the 0- to 5-cm depth, cover crop had no effects on the size of KCl-Pi fraction, whereas conservation tillage increased the pool size when compared to conventional tillage (Table 3). Tillage had no effects on the NaOH-Po fractions, while cover crop had positive effects. Moreover, marginal cover crop effects ($p = .05$) were observed for the stocks of TP. Interactions of cover crop and tillage effects were significant on the residual-P fraction in these soils at the same depth (Table 3). No tillage and cover crop effects were observed in the fractions of NaOH-Pi and HCl-Pi.

For soils at the 5- to 15-cm depth, TP ranged from 548 to 648 kg P ha^{-1} and was not different among the treatments (Table 3). Similar neutral effects were also observed for all the chemically defined pools, except for the NaOH-Pi, in which cover crop had positive effects (i.e., increased its pool size; Table 3).

Despite the changes in pool sizes described above, the contribution of the P fractions to soil TP was not affected by the treatments at both soil depths (Supplemental Table S1). Regardless of treatments and soil depths, soil TP was dominated by NaOH-Po fraction, followed by NaOH-Pi and residual P, with less than 4% in either HCl-Pi or KCl-Pi fractions (Figure 1). The percentages of NaOH-Po were averaged 63 and 48% at the 0- to 5- and 5- to 15-cm depth, respectively.

3.2 | Microbial biomass P

Conservation tillage and cover cropping did not change MBP concentration in soils at both depths (Figure 2). Regardless of

TABLE 3 Phosphorus stocks and distributions (kg ha^{-1}) in various chemically defined pools in a Norfolk soils under different management practices. Values are means with one standard error ($n = 4$). Italicized numbers are *P*-values are for the ANOVA analysis of the main effects of tillage and cover crop and their interactions

	KCl-Pi[a]	NaOH-Po	NaOH-Pi	HCl-Pi	Residual P	Total P
0- to 5-cm depth						
CS-Fallow	3 ± 0	118 ± 5	38 ± 3	5 ± 2	25 ± 1	190 ± 10
CS-Cover	4 ± 0	181 ± 16	55 ± 5	8 ± 1	31 ± 2	279 ± 21
CV-Fallow	2 ± 0	125 ± 14	41 ± 6	4 ± 2	29 ± 2	202 ± 22
CV-Cover	3 ± 1	138 ± 26	46 ± 10	5 ± 2	27 ± 1	219 ± 40
Cover	*.22*	*.04**	*.13*	*.29*	*.18*	*.05**
Tillage	*.04**	*.31*	*.63*	*.21*	*.83*	*.36*
Cover × Tillage	*.62*	*.16*	*.35*	*.60*	*.02**	*.17*
5- to 15-cm depth						
CS-Fallow	12 ± 3	307 ± 17	164 ± 18	24 ± 8	82 ± 17	589 ± 57
CS-Cover	20 ± 4	288 ± 32	219 ± 4	23 ± 6	97 ± 3	648 ± 42
CV-Fallow	13 ± 3	265 ± 32	170 ± 11	17 ± 7	83 ± 8	548 ± 24
CV-Cover	11 ± 1	292 ± 21	202 ± 30	29 ± 14	80 ± 8	614 ± 62
Cover	*.32*	*.85*	*.03**	*.54*	*.50*	*.19*
Tillage	*.14*	*.43*	*.77*	*.94*	*.36*	*.43*
Cover × Tillage	*.07*	*.34*	*.54*	*.50*	*.34*	*.94*

*Significant at the .05 probability level.

[a]Pi, inorganic P; Po, organic P; CS, conservation tillage; CV, conventional tillage; Fallow, without winter cover crops; Cover, with winter cover crops.

the management practices, MBP ranged from 6 to 8 mg kg^{-1} and 3 to 4 mg kg^{-1} at the 0- to 5- and 5- to 15-cm depths, respectively.

3.3 | Phosphatase potential activities

No cover crop effects were found at either soil depths (Figure 3). The main effects of tillage were only found significant in soils at the 0- to 5-cm depth, where implementations of conservation tillage resulted in higher phosphatase activity when compared to conventional tillage (Figure 3).

3.4 | Correlations between measured soil variables

In soils at the 0- to 5-cm depth, the fractions of KCl-Pi, NaOH-Po, NaOH-Pi, HCl-Pi, $NaHCO_3$–Pi, and $NaHCO_3$–Po were all positively correlated with each other, but none were correlated with residual P, bulk density, and soil pH (Supplemental Table S2). Phosphatase potential activity was positively correlated with KCl-Pi, TC, and TN. Nonetheless, most of the observed significant correlations at 0–5 cm were not found in soils at 5–15 cm, except that the $NaHCO_3$–Pi, $NaHCO_3$–Po, NaOH-Pi, and HCl-Pi were correlated with each other (Supplemental Table S3).

4 | DISCUSSION

In the present study, we evaluated P fractions in a Coastal Plain Ultisol under long-term CA that was driven by conservation tillage and continual soil covers (summarized in Figure 4). The results suggested that conservation tillage did not increase Po (i.e., NaOH-Po) or reduced P fixation (i.e., NaOH-Pi and HCl-Pi; Table 3). Therefore, these results did not support our hypotheses. Yet, CA did enhance readily-available Pi (i.e., KCl-Pi) by 2 kg ha^{-1}, which represents <2% of the TP (Figure 1; Table 3). Although cover cropping increased Po pool size and TP stocks in the top soils (0–5 cm), it had no effects on P fixation and availability (not supporting the hypotheses; Table 3). In addition, no cover cropping effects were found in the specific phosphatase activity, while positive effects of conservation tillage were observed only at the 0- to 5-cm depth (Figure 3). The results suggested limited effects of conservation tillage, likely confounded by the co-effects of residue returns, and additive effects of cover cropping on P stocks and availability in the tested soils.

4.1 | P distributions in chemically defined pools

In our study, P mainly existed in forms not readily available to plants with the organic fractions (i.e., NaOH-Po) dominating

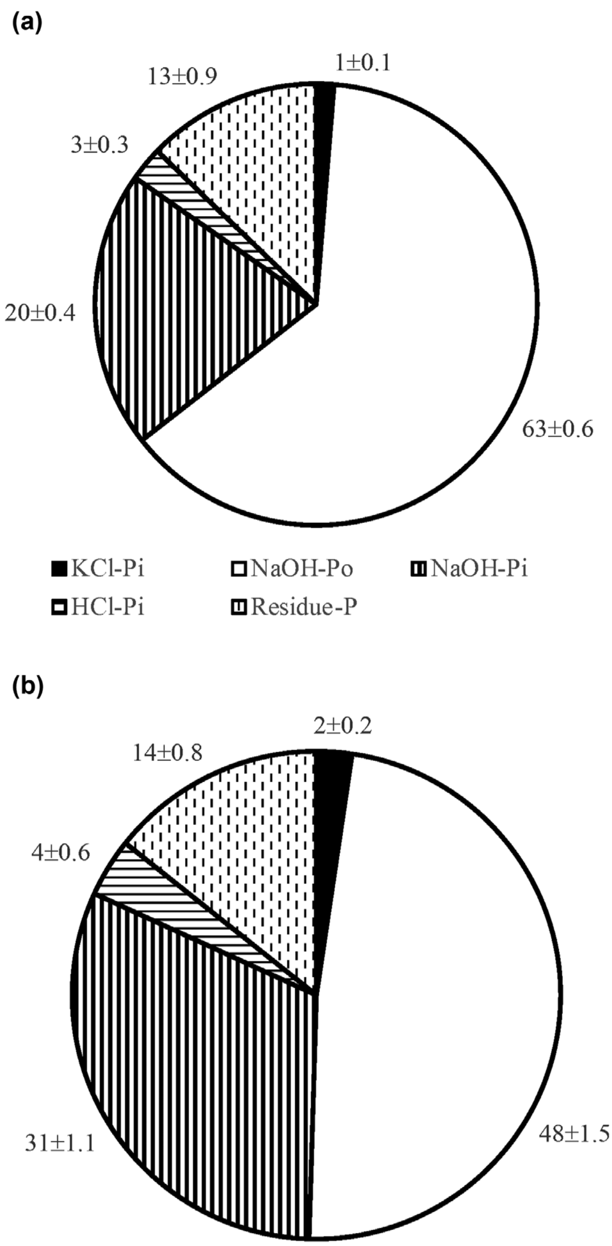

FIGURE 1 Contribution (% ± 1 standard error of the mean) of various chemically defined pools to soil total phosphorus in soils at 0- to 5- (a) and 5- to 15-cm depth (b). Pi, inorganic phosphorus; Po, organic phosphorus

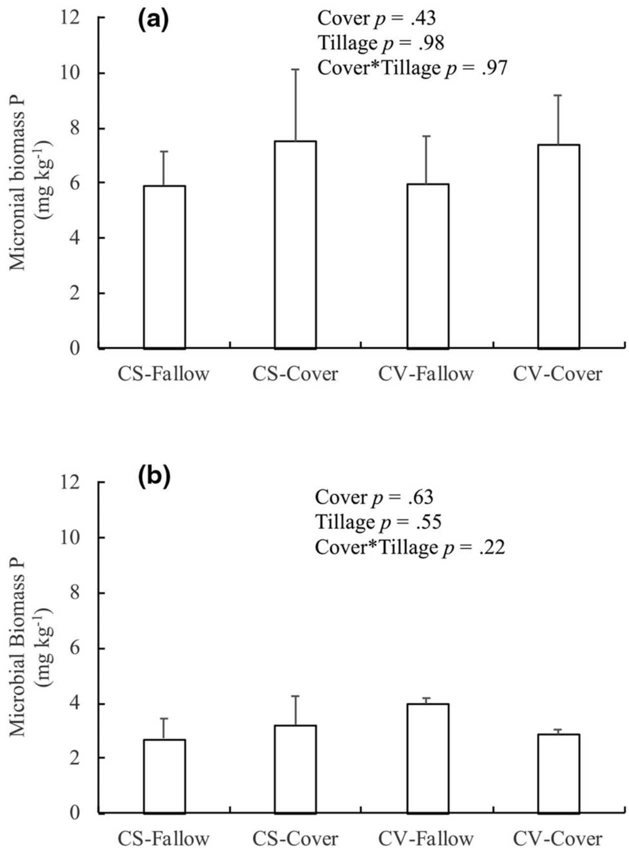

FIGURE 2 Microbial biomass P in soils under different management practices at 0- to 5- (a) and 5- to 15-cm depths (b). Bars indicate mean ±1 standard error ($n = 4$). *P*-values are shown for the ANOVA results of the main effects of tillage (Tillage) and cover crop (Cover) and their interactions (Tillage × Cover). CS, conservation tillage; CV, conventional tillage; Fallow, without winter cover crops; Cover, with winter cover crops

the pools (Figure 1; Table 3). The relatively lower percentages of P associated with primary (i.e., residual P) and secondary minerals (i.e., NaOH-Pi and HCl-Pi), especially in the top soils (0–5 cm), may be attributable to intensive clay mineral weathering and clay eluviation in soils of the Coastal Plain (Novak & Busscher, 2013; Shen et al., 2011), reducing the soils' sorption capacity (i.e., fewer clay minerals; Table 2; Novak & Watts, 2004). Despite the difference in size, these chemically defined pools are often in equilibrium with each other regulating the P availability and mobility in soils (Figure 4; Shen et al., 2011; Ye et al., 2010), which was supported by their significant correlations (Supplemental Table S2). The unchanged contributions of each pools to the TP following the increases of NaOH-Po in 0- to 5-cm soils with cover cropping (Table 3; Figure 1) further suggested the existence of equilibrium among the pools. Soil pH is a key factor to regulate the equilibrium by affecting the adsorption and desorption processes (Shen et al., 2011). However, pH appeared to have no correlations with any of the P fractions under the soil management conditions of the present study (Supplemental Tables S2, S3), indicating that pH was not relevant in controlling P fractions in this soil.

4.2 | Conservation tillage on P dynamics

Tillage can affect SOC decomposition through its effects on soil physiochemical properties and microbial activities,

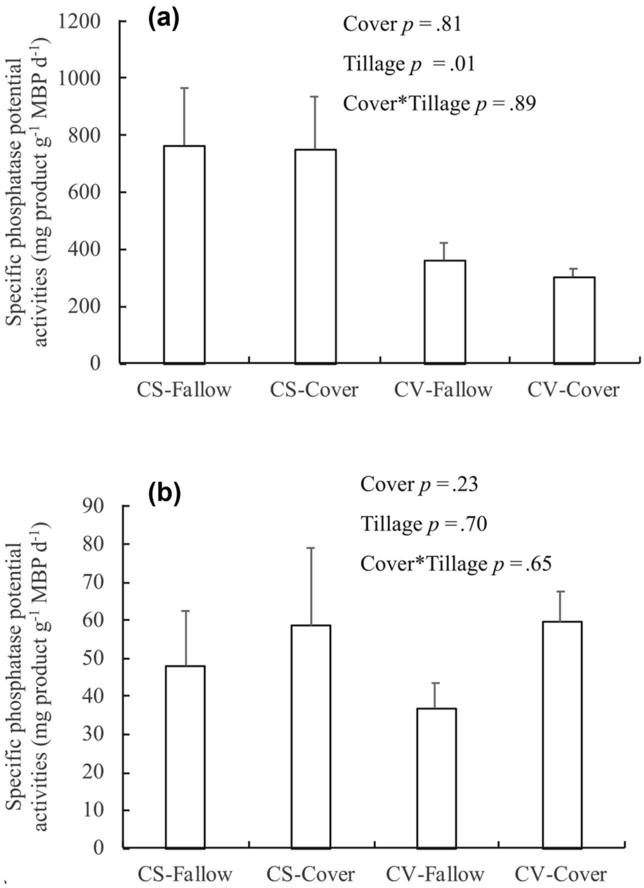

FIGURE 3 Tillage and cover crop effects on soil specific phosphatase potential activity at 0- to 5- (a) and 5- to 15-cm depths (b). Bars indicate mean ±1 standard error ($n = 4$). P-values are shown for the ANOVA results of the main effects of tillage (Tillage) and cover crop (Cover) and their interactions (Tillage × Cover). CS, conservation tillage; CV, conventional tillage; Fallow, without winter cover crops; Cover, with winter cover crops

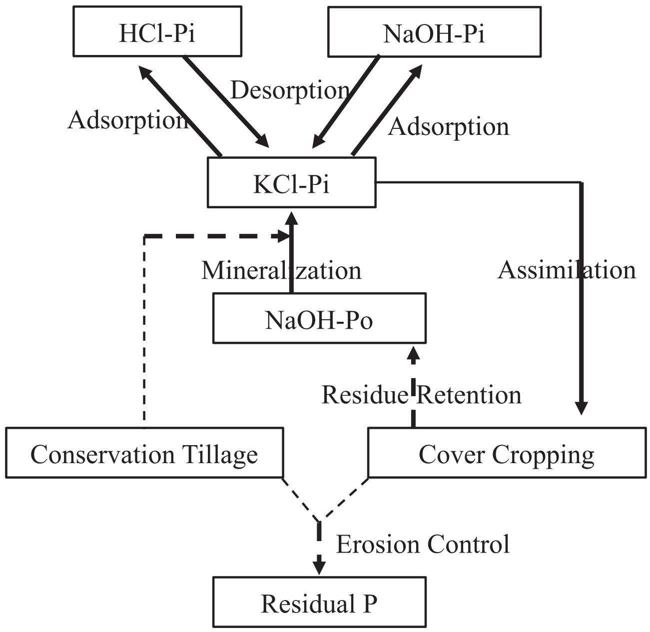

FIGURE 4 Conceptual model demonstrating P equilibrium among chemically defined fractions in soils (0–5 cm) and management impacts on their pool sizes. Dot lines suggests positive effects ($p < .05$). Pi, inorganic phosphorus; Po, organic phosphorus

which in turn affect the transformation, distribution, and availability of P in soils (Margenot et al., 2017; Rodrigues, Pavinato, Withers, Teles, & Herrera, 2016; Wei et al., 2014). For instance, tillage destroys soil structure or aggregation promoting P adsorption by increasing relative soil surface area (Wei et al., 2014). Therefore, the observed neutral tillage effects on the stocks of Pi fractions associated with secondary minerals (i.e., NaOH-Pi and HCl-Pi) were likely a result from no improvements in soil structure or aggregation (estimated by mean weight diameter; Table 2). However, the relatively low soil clay contents (i.e., less absorption capacity and aggregation "building blocks") may also partially explain this outcome (Table 2).

It was unexpected that conservation tillage did not increase NaOH-Po stocks (Table 3), especially when significant accumulations of SOC were observed in the top soils (0–5 cm; Table 2). Similar results were also reported in three Ultisols under no-till resulting in lower organic P/SOC ratios (Weil, Benedetto, Sikora, & Bandel, 1988). The dynamics of soil Po are less understood when compared to Pi (Turner, Condron, Richardson, Peltzer, & Allison, 2007; Wei et al., 2014). Despite the uncertainties, NaOH-Po is considered an important source of available P for crops (Kuo et al., 2005; Margenot et al., 2017; Takeda et al., 2009). It is believed that NaOH-Po is closely associated with humic compounds in the form of organic matter-P complexes possibly through Fe and Al bridges (Borie & Zunino, 1983; Schoenau, Stewart, & Bettany, 1989). After surveying several similar studies, Kuo et al. (2005) regressed the $NaHCO_3$–Po against NaOH-Po concentrations and found that where Po was an important source of available P; the ratio was around 25%. This compared with 23 and 13% for the tested soils at 0–5 and 5–15 cm (Tables 2 and 3), suggesting the mineralization of Po in the top soils can be sources of P for plants and leaching as well, which may also explain why the higher NaOH-Po in the top soils was accompanied with higher NaOH-Pi in subsurface soils under cover cropping (Table 3).

Higher phosphatase activity has been frequently reported in soils with conservation tillage than in soils under conventional tillage (Deng & Tabatabai, 1997; Hu et al., 2015; Wei et al., 2014). This enzymatic activity was also observed in the present study, but only in top soils (0–5 cm; Figure 3). Interestingly, the specific phosphatase activity (per MBP) was correlated with TC ($r = .91, p < .01$), but not with the size of NaOH-Po fraction (Supplemental Table S2). These results suggest that the observed increased phosphatase activity was not caused by higher organic P (i.e. substrate) availability, but likely by higher overall microbial activity that resulted from the accumulation of SOC in the top soils (Table 2). This result was further supported by the higher microbial biomass C and respiration in soils under conservation tillage than soils under conventional tillage (data not shown). Significant positive correlations between phosphatase with SOC has already been documented (Deng & Tabatabai, 1997), further supporting the possibility that C inputs through crop residues enhanced the mineralization of soil Po (Bünemann, Steinebrunner, Smithson, Frossard, & Oberson, 2004; Takeda et al., 2009).

Both MBP and phosphatase activity are considered good indicators of P mineralization potentials and availability in agricultural soils (Shi, 2011). The higher phosphatase activity observed in soils under conservation tillage suggested more Po was mineralized when compared to soils under conventional tillage (Shi, 2011; Takeda et al., 2009), supported by their higher KCl-Pi concentrations (Figure 4; Table 3), which may also explain why the Po was not increased along with TC in the top soils under long-term conservation tillage (Table 3). Nonetheless, no tillage effects were found in MBP (Figure 2), suggesting the increased TC in soils did not promote the assimilation of P in biomass rather than increased metabolic activities (Figure 3). Despite accounting for a small fraction (2–5%) of soil TP, MBP is often considered an important source of P for plants, especially in P-fixing soils (Brookes, 2001; Chen, He, & Huang, 2000). In the present study, MBP was 1–4% of the soil TP and hence a significant pool in the tested soils.

4.3 | Cover cropping and P fractions

Limited studies have demonstrated the increases of P availability and mineralization in soils with cover crops (Kuo et al., 2005; Redel, Rubio, Rouanet, & Borie, 2007; Takeda et al., 2009). However, such effects were not observed in the present study (Table 3; Figures 2 and 3). Instead, the effects were mostly observed in the fractions of NaOH-Po and TP in top soils. Both positive and neutral effects of cover cropping on Po stocks have been reported (Kuo et al., 2005; Redel et al., 2007), highlighting the broad spectrum of Po compounds that differ remarkedly in their chemistry and behavior in soils and hence the extent to which they respond to changing environments (Turner et al., 2007; Wang et al., 2013; Wei et al., 2014). Intriguingly, the increases of NaOH-Po were not accompanied with the increases of TC (Tables 2 and 3) in top soils. Although the correlation between NaOH-Po and TC was positive (Supplemental Table S2), the enhanced Po stocks were not mainly driven by organic inputs (i.e., residue returns). During cover cropping, no P was added externally. Cover crops take up P derived from the decomposition of SOC and crop residues and return P back to soils in the forms of residues (Figure 4). Although cover crop biomass production was not available for these plots, the production of a similar mixture in adjacent fields (<1 km) resulted in estimated 6–8 kg ha^{-1} of residue Po into soils annually (Nash et al., 2018; Ye et al., 2019). However, the observed increased Po stock can be also attributable to the possibility that cover cropping reduced the losses of labile Po from the top soil by leaching or surface runoff (Djodjic et al., 2006; King et al., 2015).

Interestingly, higher residual P stock was found in soils at 0–5 cm only when cover cropping was implemented together with conservation tillage (Table 3). Residual P is an unavailable pool and stable against microbial decomposition, but may be susceptible to losses via surface run-off and soil erosion that can be reduced by minimal soil disturbance (e.g., conservation tillage) and soil cover (e.g., cover cropping; Palm et al., 2014). Therefore, it is plausible that the higher residual P in the soils at 0–5 cm was the result of the cover cropping × conservation tillage interaction.

5 | CONCLUSION

Both conservation tillage and cover cropping affected P fractions in the tested soils, but by different mechanisms. Long-term (~40 yr) conservation tillage improved phosphatase potential activity in the surface soils (0–5 cm) through its effects on microbial communities by increasing SOC (i.e., carbon substrates), which concurrently resulted in positive but limited effects on the pool sizes of the readily available P (i.e., KCl-Pi). The integration of winter cover crops along with conservation tillage and residue returns for four years have increased the size of organic (i.e., NaOH-Po) and nonlabile fractions (i.e., residual P) resulting in higher TP stocks. It is likely that the P assimilated by the cover crop was released from the decomposition of cash crop residues and returned back to the soil in organic P form. Despite all the observed fraction changes, the chemically defined P pools were in equilibrium with each fraction, resulting in stable contributions of each pool to the TP that was dominated by organic P (i.e., NaOH-Po). The mineralization of Po in the top soils can be a major source of P for plants. In short, using winter cover crops is a good management practice to improve P stocks and availability in the sandy agricultural soils of the southeastern Coastal Plain of the United States. However, management practices such as using high residue crop rotation or increasing cover crop biomass production are needed to enhance SOC deeper in the soils, and thus improve the desirable outcomes throughout the plant rooting depth.

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