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ORIGINAL ARTICLE

Phosphorus dynamics and phosphatase activity of soils under corn production with supplemental irrigation in humid coastal plain region, USA

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Abstract A 3-year (2013–2015) field study was conducted to evaluate the effect of integrated nutrient management (NM) and three irrigation scheduling methods (IS): irrigator pro (IPro); normalized difference vegetative index (NDVI) and soil water potentials (SWP) on phosphorus (P) dynamics and phosphatase activity in four Coastal Plains soil types (ST) at various growth stages (CS: V6, six leaves; V16, sixteen leaves; and R1, silking) of corn (*Zea mays* L.). Nitrogen fertilizer was applied at two rates: 157 and 224 kg ha^{-1} through the irrigation system in three applications. Phosphorus dynamics and phosphatase activity varied significantly ($p \leq 0.0001$) with year (Y), CS and ST, but not with NM. Phosphorus uptake of corn had an increase of about 1200% from V6 to R1. Both the Mehlich extractable P and water soluble P showed declining trends from V6 to R1. Concentration of P in pore water differed significantly ($p \leq 0.05$) with IS in 2014 and 2015, but not in 2013. The order of the concentrations of P in pore water (averaged across ST) as affected by IS is as follows: 2013 (IPro = NDVI = SWP); 2014 (SWP = IPro < NDVI); and 2015 (IPro < NDVI < SWP). Concentration of phosphatase among the different ST was affected by CS, from V6 to R1 and soil depth, but not with NM. The difference in phosphatase concentration between the upper and lower soil horizons (averaged across Y and ST) was about 67.7 µg g^{-1} h^{-1}. Our results have significant implication on P mobility, availability and management in areas where inputs of P in fertilizers may have had exceeded P output in harvested crops. Our results further suggest that understanding of P inputs and outputs which include P accumulation in soils and plants, as well as P losses is critical to determining the environmental balance and accountability of P in agricultural ecosystem. It is imperative to have a holistic understanding of P dynamics from soil to plant by optimizing P management and improving P-use efficiency.

Keywords Phosphorus · Phosphatase activity · Coastal plain region · Corn · Irrigation scheduling · Soil types · Silking · Nutrient use efficiency · Water use efficiency

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Introduction

Soil P exists in various chemical forms including both inorganic P and organic P. These P forms differ in their behavior and chemical fate in soils (Hansen et al. 2004; Turner et al. 2007). Phosphorus dynamics in the soil–plant system is a function of the integrative effects of P transformation, availability and utilization caused by soil, rhizosphere and plant processes (Shen et al. 2011). Critical to determining environmental balance and accountability is an understanding of P inputs and outputs in agricultural ecosystem which include among others, P accumulation by plants and P losses. Phosphorus losses from soils by both leaching and runoff results in inefficient utilization of P fertilizer and increased risk of eutrophication of rivers and estuaries (Berkheiser et al. 1980; Enfield and Ellis 1983; Sigua et al. 2005). Further research effort on simultaneous intensification of crop production and water quality protection with supplemental irrigation is therefore warranted.

Irrigation management for corn (*Zea mays* L.) production in the southeastern Coastal Plain region of USA is difficult because of the highly variable climate along with typical low water holding capacity and low fertility of the soils. Despite of the variety of methods and tools developed to schedule irrigation, farmer adoption of irrigation scheduling technique is still limited because variability of rainfall is often difficult to adequately accommodate in the planning of irrigation calendar (Stone et al. 2015, 2016). However, water shortage often causes nutrient deficiency particularly P (Clarke et al. 1990; Recio et al. 1999; Haefele et al. 2006). Therefore, integrated effect of P fertilization and irrigation scheduling may improve the nutrient uptake increase in grain weight and yield of cereal crops (Hossain et al. 1996; Turk and Tawaha 2002; Yousaf et al. 2014). Future climate change could have the potential to significantly alter the conditions for crop production, with important implications of irrigation management for worldwide food security (Rosenzweig and Hillel 1998; Afandi et al. 2010).

Phosphorus plays an important function in plant physiology of most cereal crops including corn. It strengthens the straw and increase formation and fruit production. However, when it is applied to soil, it may become fixed and a limiting factor to crop growth and productivity (Mandal and Khan 1972). With increasing demand of agricultural production due to global increase of population in the next decade, P is receiving more attention as a nonrenewable resource (Cordell et al. 2009; Gilbert 2009). One aspect of P dynamics that is very seldom mentioned is the role of phosphatase enzyme in the soils. Phosphatase activity is strongly regulated by P addition to the soil and it is possible that production of phosphatase may also play important role in the regulation of P supply to plants (Olander and Vitosek 2000). Although phosphatase activity has been extensively studied in soils as shown by some reviews (Malcom 1983; Tabatabai 1994), very limited information is available on how irrigation and other agricultural management were affecting its functionality in the soils. Phosphatase enzyme catalyzes the hydrolysis of ester-phosphate bonds, leading to the release of phosphate, which can be taken up by plants or microorganism (Nannipieri et al. 2011). There have been fewer investigations concerning ecological agriculture and enzyme activity. Enzyme activity is also influenced by plants because they have been shown to stimulate the activity of enzymes in the rhizosphere and can be higher activity in planted than in unplanted soils. On the other hand, there are also some inhibitors of enzyme activity. The claim that phosphatase activity can be depressed by phosphate fertilizers and N fertilizers with similar effect on enzymes involved in the nitrogen cycle and these nutrients may warrant additional investigation.

Application of commercial P fertilizers to agricultural land in the past decades have improved soil P fertility and crop yields, but also contributed to P pollution in waterways (Shigaki et al. 2006; Sigua et al. 2011). The rate at which soil P accumulates in terrestrial ecosystem especially under irrigation system is still uncertain, as are the mechanisms responsible for the current P sink and/or source (Sigua et al. 2009, 2011). Aiming at reducing consumption of chemical P fertilizer, it is imperative to have a holistic understanding of P dynamics from soil to plant by optimizing P management and improving P-use efficiency. Additionally, the dynamics of applied P in soils and its cycling in agroecosystems are of increased interest due to its contribution to the current environmental, agronomic and economic issues on intensification of agricultural production (Sharpley and Turnley 2000). Our objective for conducting this study was to determine the effect of integrated nutrient management and irrigation scheduling on P dynamics and phosphatase activity of soils at various growth stages (V6, V16 and R1) of corn (*Zea mays* L.) production in humid southeastern Coastal Plain region of United States.

Materials and methods

Site description

From 2013 to 2015, corn (*Zea mays* L.) was grown under conservation tillage on a 6-ha site under a variable-rate center pivot irrigation (VRI) system near Florence, South Carolina. Each year, field preparation started with an application of glyphosate herbicide to control winter weeds. Field tillage at corn planting consisted of in-row sub-soiling. Corn (Dekalb 66-97 in 2012, 2013 and 2014) was planted in 76 cm rows, with a planting population of 79,000 seeds per hectare. The planting dates for the 3 years were: 03/30/2013; 04/09/2014; and 04/04/2015. The corn field received an annual lime application of 1.7 tons ha^{-1} in 2013 and 2014. Phosphorus and potassium fertilizers were also applied in blanket application at the rate of 118 kg P_2O_5 ha^{-1} and 135 kg K_2O ha^{-1} in 2013, 2014 and 2015, respectively. The monthly average rainfall and the amount of irrigation application in the study site during the growing season of corn from 2013 to 2015 are presented in Fig. 1.

Experimental treatments and experimental design

The layout of our experimental plots (9.1 × 9.1 m plot) was based on split–split-split plot in complete block design (Fig. 2). Experimental treatments were consisted of four factors: four soil types (ST); three irrigation scheduling method (ISM); two nitrogen management (NM); and two soil depths (SD). These different treatments are further described below. Additionally, Fig. 2 shows the different locations of ST (main treatment) within the 6-ha site under a variable rate irrigation (VRI) system. The three sub-treatments consisting of ISM, NM and SD were randomly distributed under each ST with three replications shown in Fig. 2. Detailed descriptions of the different experimental treatments (ST, ISM, NM and SD) are described below.

Soil types (ST) treatment

Soils under the center pivot irrigation system are highly variable. These soils consisting of four ST are as follows: (1) Bonnaeau, BnA; loamy, siliceous, subactive, thermic Arenic Paleudults; (2) Norfolk, NkA; fine loamy, kaolinitic, thermic Typic Kandiudults; (3) Dunbar, Dn; fine loamy, kaolinitic, thermic, Aeric Paleaquults; and (4) Noboco, NcA; fine loamy, siliceous, subactive, thermic Oxyaquic Paleudults (Fig. 2). These four ST belong to the Ultisol Soil Order (Soil Taxonomy) and formed extensively from weathered Coastal Plain marine sediments with low soil fertility and poor water holding capacity. Some of the selected properties of the different ST used in our study are shown in Table 1.

Each experimental plot (9.1 × 9.1 m) represented by four ST was instrumented with suction lysimeter and soil moisture tensiometer. Suction lysimeters were

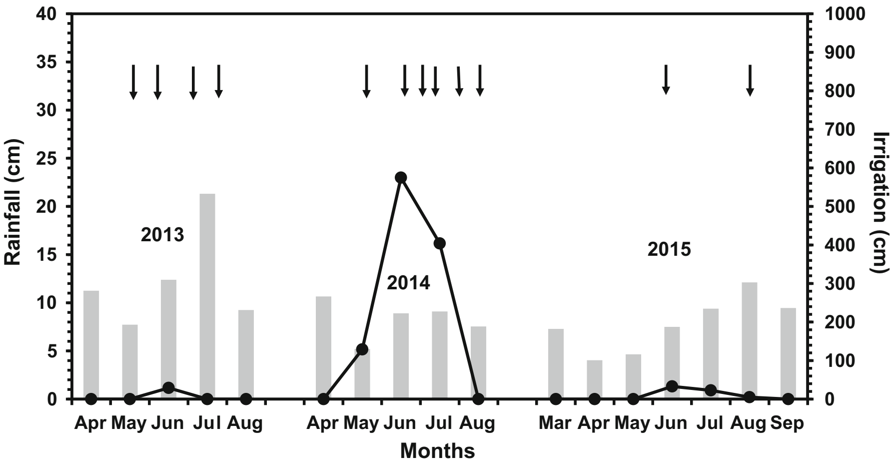

Fig. 1 Average monthly rainfall distribution (represented by bars), irrigation amount (represented by solid lines) and sampling dates for pore water (represented by downward arrow) in the study site during the growing season of corn (2013–2015)

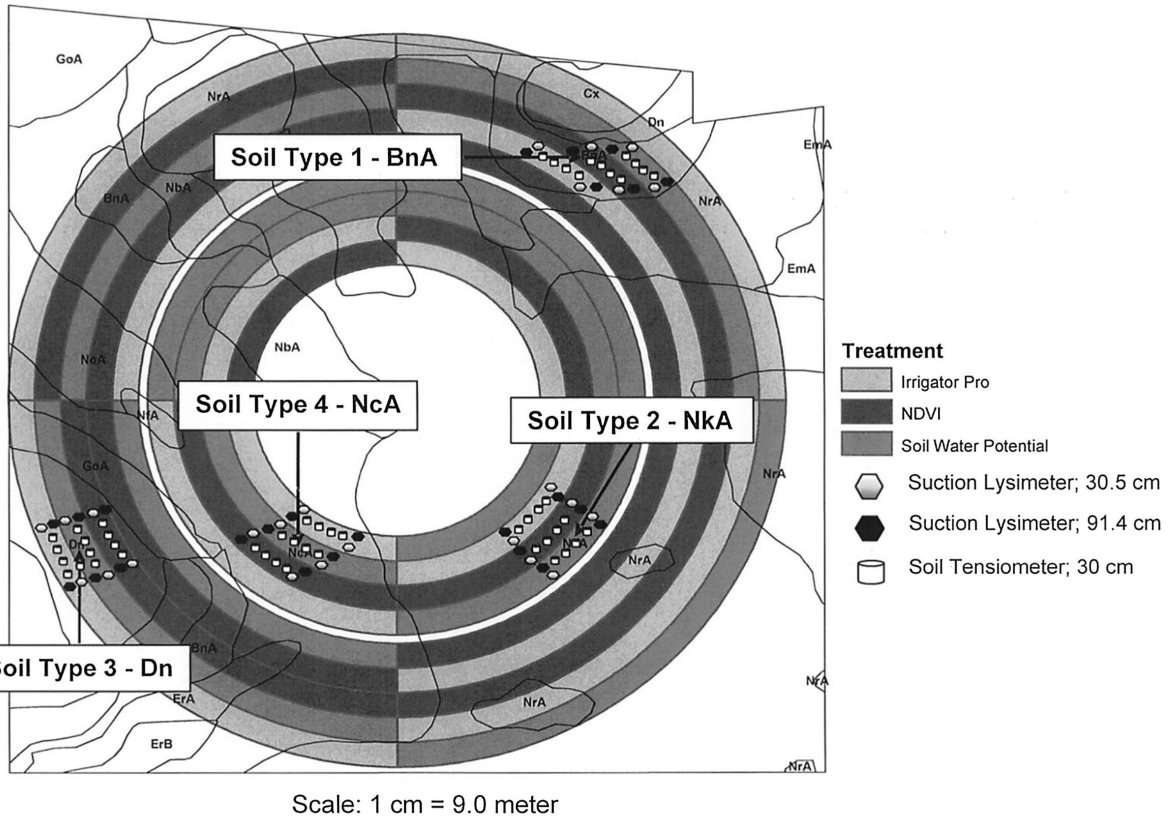

Fig. 2 Plot map showing the different soil types included in the study and different irrigation scheduling methods under the pivot irrigation system (*Source*: Sigua et al. 2016. Agric. Water Manage. 186:75–85)

installed at two depths (i.e., 30.5 and 91.4 cm) while soil tensiometer were installed at 30 and 60 cm soil depth. Additional descriptions on the installations of suction lysimeter and soil tensiometer can be found in early paper reported by Sigua et al. (2017).

Center-pivot irrigated system and irrigation scheduling method (ISM) treatment

Irrigation was performed with a center pivot irrigation system modified to permit variable application depths to individual areas of about 9.1 × 9.1 m in size (Omary et al. 1996). The center pivot length (137 m) was divided into 13 segments, each 9.1 m in length. Variable rate water applications were accomplished by using three manifolds in each segment; each had nozzles sized to deliver 1×, 2×, or 4× of a base application depth at that location along the center pivot length. A more detailed description of the water delivery can be found in Omary et al. (1996), Stone et al. (2015) and Sigua et al. (2017).

Three methods of irrigation scheduling treatments were evaluated for our study. These three methods of irrigation scheduling treatments were reported in early paper of Sigua et al. (2017). Irrigation scheduling methods under the center pivot irrigation system was replicated three times and was randomly arranged on every quadrant as shown in Fig. 2. The first irrigation treatment was based on the Irrigator Pro for Corn expert system (IPRO) that was developed by the USDA-ARS-National Peanut Research Laboratory, Dawson, GA. This expert system has been tested extensively in uniformly irrigated fields (Davidson et al. 1998a, b; Lamb et al. 2004, 2007). In this research, IPRO for corn was implemented using spatial management zones corresponding to variable ST. Irrigator Pro uses soil texture and soil water potential measurements to estimate the soil water holding capacity in the root zone for water balance calculations.

The second irrigation treatment (Soil Water Potential, SWP) treatment) was based on using soil water

Table 1 Selected properties of the different soils (BnA, NkA, Dn and NcA) that were used in the study

Soil Properties	Bonneau soil (BnA)	Norfolk soil (NkA)	Dunbar soil (Dn)	Noboco soil (NcA)
1. Physical properties				
Sand (g kg^{-1})	710	807	604	755
Silt (g kg^{-1})	190	167	207	180
Clay (g kg^{-1})	100	26	169	85
2. Chemical properties				
pH	5.5	5.2	5.2	4.6
EC (dS m^{-1})	0.105	0.115	0.109	0.116
Total C (g kg^{-1})	7.2	5.8	13.8	8.3
Total N (g kg^{-1})	0.5	0.8	0.1	0.6
P (mg kg^{-1})	50.9	20.3	95.4	39.6
K (mg kg^{-1})	53.9	121.5	168.3	77.3
Ca (mg kg^{-1})	247.6	244.5	419.4	484.9
Mg (mg kg^{-1})	55.6	54.7	113.2	74.1
Na (mg kg^{-1})	37.1	29.6	34.8	35.9
Al (mg kg^{-1})	687.3	924.7	1062.7	924.4
Fe (mg kg^{-1})	25.1	10.7	23.6	21.6
Cu (mg kg^{-1})	0.31	0.18	0.19	0.61
Zn (mg kg^{-1})	4.8	3.8	3.5	4.1

Bonneau soil (BnA)—loamy, siliceous, subactive, thermic Arenic Paleudults

Norfolk soil (NkA)—fine loamy, kaolinitic, thermic Typic Kandiudults

Dunbar soil (Dn)—fine loamy, kaolinitic, thermic, Aeric Paleaquults

Noboco soil (NcA)—fine loamy, siliceous, subactive, thermic Oxyaquic Paleudults

potential sensors to maintain soil water potentials (SWP) above −30 kPa (approximately 50% depletion of available water) in the surface 30 cm of soils within a plot. Soil water potentials were measured from 12 sites within each soil type shown in Fig. 2. In each treatment and replication, tensiometers (Soilmoisture Equipment Corp., Santa Barbara, CA) were installed in the individual ST within each plot at two depths (30 and 60 cm). Measurements were recorded at least three times each week. The 30-cm tensiometer in the SWP treatment was used to initiate irrigation applications. When the soil water potential of the SWP treatments decreased below − 30 kPa, a 12.5-mm irrigation application was applied to that plot. Additionally, if soil water potentials decreased below − 50 kPa, an additional 12.5 mm of irrigation was applied if the rainfall forecast was less than 50%.

The third irrigation treatment was based on remotely sensing the crop normalized difference vegetative index (NDVI treatment). The NDVI treatment was used to estimate crop coefficients using methods similar to those used by Bausch (1993) and Glenn et al. (2011). These estimated crop coefficients will then be used in the FAO 56 dual crop coefficient method for estimating crop evapotranspiration (ET_c) and irrigation requirements. Initially in 2012, the crop coefficients were based on the FAO 56 crop coefficients for field corn ($K_{cb\ ini} = 0.15$, $K_{cb\ mid} = 1.15$, and $K_{cb\ end} = 0.5$).

Nitrogen management treatment (NM)

Nitrogen fertilizer was applied at the rate of 157 and 224 kg N ha^{-1} through the irrigation system in three applications. The lower rate (157 kg N ha^{-1}) of nitrogen application is the recommended rate of nitrogen application for non-irrigated maize production in Coastal Plain region. The higher rate (224 kg N ha^{-1}) of nitrogen application is the recommended rate of nitrogen application for irrigated maize production in Coastal Plain region. All nitrogen fertilizer, except pre-plant granular applications, was applied via fertigation.

Collection of pore water

The two depths where pore water samples were collected as samples become available were 30.5 and 91.4 cm, respectively. Pore water sample from the suction lysimeter was collected from sampling sites shown in Fig. 2 using a flask with two-hole rubber stopper. One hole was directly connected to the plastic tubing from the sampler and one hole was connected to the hand vacuum pump. Stroking the hand pump created vacuum within the flask which in turn withdraws the sample up from the sampler and into the collection bottle. Suction lysimeter were completely evacuated 1 day before the sampling process to ensure that the water samples are fresh and acceptable for chemical analysis. Figure 1 shows the different sampling dates (shown by down arrows) for leached or pore water in the study site during the growing season of corn. Total number of pore water samples collected in 3 years (2013–2015) from four ST of BnA, NkA, Dn and NcA were 113, 97, 96 and 110, respectively.

Analyses of pore water samples

Pore water samples were transported to the laboratory following collection and refrigerated at 4 °C. Water samples were filtered using a 0.2 µm nylon filter and were analyzed for total P using an Inductively Coupled Plasma Spectroscopy (ICP).

Soil sampling and soil analysis

The different sampling locations represented by four ST are shown in Fig. 2. Soil samples were collected at 0–15 and 15–30 cm during the three stages of corn growth namely: V6: 6 leaves; V16: 16 leaves; and R1: silking). A total of 576 soil samples (soil type = 4; soil depth = 2; growth stage = 3; nutrient management = 2; year = 3; replications = 4) were collected from 2013 to 2015.

Soil samples were air-dried and passed through a 2-mm mesh sieve prior to extraction of soil P. Soil P was extracted separately with deionized distilled water (1:5 soil:DI) for water soluble concentration of P (WSP) and with double acid ($0.025\ \underline{\text{N}}\ H_2SO_4 + 0.05\ \underline{\text{N}}\ HCl$; Mehlich 1953) for the extractable concentration of P (MEP). These two extracts were analyzed separately by Inductively Coupled Plasma (ICP) spectroscopy. Soil samples were also analyzed for the concentration of P enzyme (acid phosphatase) following the procedures described by Eivazi and Tabatabai (1977).

Plant sampling, phosphorus tissue analysis and phosphorus uptake

Aboveground biomass of ten corn plants was collected at three stages of corn growth (V6: 6 leaves; V16:16 leaves; R1: silking). Freshly cut aboveground biomass was oven-dried at 60 °C for about 48 h. Aboveground biomass was ground to pass through 1-mm mesh screen in a Wiley mill. Ground samples were digested in an auto-block using a mixture of nitric and peroxide and were analyzed for tissue P concentration using an ICP spectroscopy. Phosphorus uptake of corn at three growth stages (i.e., V6, V16 and R1) was calculated using Eq. 1 as shown below.

$$\mathrm{PU_{CS}} = [\text{Concentration of Phosphorus, } \mathrm{CP_{CS}}] \times \mathrm{ABY_{CS}} \tag{1}$$

where $\mathrm{PU_{CS}}$, phosphorus uptake (kg $\mathrm{ha^{-1}}$) of corn at various growth stages; $\mathrm{CP_{CS}}$, P concentration (%) of corn tissues at various growth stages of corn; and $\mathrm{ABY_{CS}}$, aboveground biomass (kg $\mathrm{ha^{-1}}$) of corn at various growth stages of corn.

Data reduction and statistical analysis

Data (concentrations of P in plants, soils, pore water; P uptake; phosphatase activity) were analyzed with a five-way ANOVA using PROC GLM (SAS 2000). The model included soil type (ST), irrigation scheduling (IS), nutrient management (NM), soil depth (SD) and growth stage (CS). The pooled data (2013–2015) were tested initially for normality (SAS 2000). For this study, *F* test indicated a significant ($p \leq 0.0001$) year (Y) effect, so means of ST, IS, NM, SD and CS on concentrations of P in pore water, soils, plants, P uptake and phosphatase activity were separated following the least significance difference (LSD) test by year (SAS 2000).

Relationships of P uptake of corn and soils' MEP and WSP with growth stages of corn in four ST from

2013 to 2015 were determined following the principles of SAS PROC REG (SAS 2000). Regression analyses for P uptake, soil's MEP and soil's WSP with growth stages of corn were based on the corresponding number of days after emergence (DAE) of corn to reflect V6, V16 and R1 growth stages as 14, 56 and 68 DAE, respectively.

Results

Concentration of P in corn tissues and P uptake of corn

Both the concentration of P and P uptake of corn varied significantly ($p \leq 0.0001$) with Y, ST, CS. However, the concentrations of P in corn tissues and P uptake of corn (averaged across Y, ST, IS and CS) were not affected by NM at all years (2013–2015). The greatest concentration of P in corn tissues of about 3475 ± 1272 mg kg^{-1} was in 2013 from BnA soil while the lowest concentration was in 2014 from NkA soil (2248 ± 1398 mg kg^{-1}). Dn soil in 2014 had the greatest uptake of P (21.2 ± 17.4 kg ha^{-1}) while BnA soil in 2013 (6.9 ± 5.5 kg ha^{-1}) had the lowest P uptake (Table 2).

Concentrations of P in tissues of corn was significantly ($p \leq 0.05$) affected by IS in 2014, but did not vary significantly with irrigation scheduling method in 2013 and 2015 (Table 2). In 2014, corn plants with IPro (2599 ± 1468 mg kg^{-1}) had the greatest concentration of P in their tissues followed by SWP (2540 ± 1600 mg kg^{-1}) and NDVI (2417 ± 1540 mg kg^{-1}). On the other hand, corn uptake of P was significantly affected by the different IS in 2013, 2014 and 2015 (Table 2). The greatest P uptake of corn in 2013 and 2014 was from plots with IPro irrigation with mean value of 8.9 ± 7.5 and 17.2 ± 15.2 kg ha^{-1}, respectively. In 2015, P uptake (kg ha^{-1}) was in this order: SWP (14.8 ± 8.8) > NDVI (13.5 ± 7.6) = IPro (12.6 ± 6.7).

From 2013 to 2015, both the concentration of P in corn tissues and P uptake of corn were affected significantly by CS. Overall, P uptake increased from V6 to R1 (Table 2). Concentration of P in tissues of corn when averaged across years (2013–2015) ranged from 4090 ± 641 to 1025 ± 416 mg kg^{-1}, which is equivalent to about 75% reduction in P concentration from V6 to R1 (Table 2). Phosphorus uptake of corn had an increase of about 1200% from V6 (3.1 ± 1.9 kg ha^{-1}) to R1 (40.3 ± 5.7 kg ha^{-1}). Figure 3 shows the P uptake of corn in different ST from V6 to R1. Again, P uptake of corn demonstrated a remarkable increase from V6 to R1. This trend supported the overall significant effects of the different ST on P uptake of corn as described above. Regression models presented in Fig. 3 showed an overall linear trend for the cumulative P uptake of corn from V6 to R1in four ST, respectively. The different regression models describing P uptake of corn at various stages of growth (V6, V16 and R1) varied remarkably among the different ST: (BnA = 13.3x − 8.5; $R^2 = 0.98$; Dn = 19.9x − 15.9; $R^2 = 0.99$; NcA = 18.2x − 15.7; $R^2 = 98$; Nka = 16.6x − 10.7; $R^2 = 0.97$; where x is the number of days after emergence of corn).

Concentrations of P in Soils: Mehlich Extractable P and Water Soluble P

Mehlich extractable P (MEP)

Concentration of MEP was significantly ($p \leq 0.0001$) affected by Y, ST, IS and CS. However, concentrations of MEP in soils (averaged across Y, ST, IS and CS) was not affected by NM at all years (Table 3). The concentration of MEP when averaged among years (2013–2015) showed that BnA (50.0 ± 22.9 mg kg^{-1}) had the greatest concentration followed by Dn (46.3 ± 27.2 mg kg^{-1}), NkA (42.6 ± 21.4 mg kg^{-1}) and NcA (36.8 ± 18.4 mg kg^{-1}). In 2013, 2014, and 2015, BnA had the greatest concentration of MEP with mean values of 70.2 ± 23.8, 35.3 ± 12.9 and 44.4 ± 13.7 mg kg^{-1}, respectively (Table 3). Unlike the effect of ST, IS effect on MEP was only significant ($p \leq 0.05$) in 2013 and 2014 where IPro and NDVI had comparable mean values of 64.3 ± 19.9 and 62.6 ± 31.4 mg kg^{-1}, respectively (Table 3). The concentration of MEP in 2013 was about 57.8 ± 27.9 mg kg^{-1}.

Soil MEP varied significantly ($p \leq 0.0001$) with soil depth. Concentration of MEP (averaged across Y, ST, and CS) in the upper soil depth (0–15 cm) was significantly ($p \leq 0.05$) greater than the concentration of MEP in the lower soil depth (15–30 cm) with values of 48.4 ± 20.9 and 35.4 ± 21.2 mg kg^{-1}, respectively (Table 3). Result is suggesting that at any given ST and year, concentration of MEP remained to be significantly higher in the upper soil layer and this could have had

Table 2 Concentration of phosphorus in tissues and phosphorus uptake of corn grown in four soil types under different nutrient management and irrigation scheduling (2013–2015)

Treatments	Year 1 (2013)		Year 2 (2014)		Year 3 (2015)	
	PP (mg kg^{-1})	PU (kg ha^{-1})	PP (mg kg^{-1})	PU (kg ha^{-1})	PP (mg kg^{-1})	PU (kg ha^{-1})
1. Soil type						
a. BnA	3475 ± 1272a[§]	6.9 ± 5.5c	2474 ± 1624b	13.4 ± 13.7c	2672 ± 1295b	13.1 ± 7.3b
b. Dn	2654 ± 759d	9. 5 ± 7.9a	2858 ± 1636a	21.2 ± 17.4a	2668 ± 1176b	14.2 ± 7.3b
c. NcA	2945 ± 1001c	8.8 ± 7.5ab	2495 ± 1439b	18.7 ± 16.7b	2829 ± 1361a	10.3 ± 7.3c
d. NkA	3114 ± 1238b	7.7 ± 6.1bc	2248 ± 1398c	16.4 ± 18.3b	2594 ± 1161b	16.9 ± 7.9a
$LSD_{0.05}$	163.7	1.2	148.9	2.5	122.2	1.9
2. Irrigation Sched.						
a. IPro	3062 ± 1129a	8.9 ± 7.5a	2599 ± 1468a	17.2 ± 15.2a	2672 ± 1245a	12.6 ± 6.7b
b. NDVI	3072 ± 1106a	7.6 ± 6.6b	2417 ± 1540b	18.2 ± 18.7a	2670 ± 1235a	13.5 ± 7.6ab
c. SWP	3007 ± 1134a	8.1 ± 6.4ab	2540 ± 1600ab	17.1 ± 16.3a	2732 ± 1267a	14.8 ± 8.8a
$LSD_{0.05}$	141.7	1.1	128.9	2.2	105.8	1.6
3. Nutrient Mgt.						
a. 157 kg N ha^{-1}	3072 ± 1101a	–	2550 ± 1562a	–	2686 ± 1221a	–
b. 224 kg N ha^{-1}	3022 ± 1135a	–	2487 ± 1503a	–	2696 ± 1268a	–
$LSD_{0.05}$	404.6		505.2		410.4	
4. Corn stage						
a. V6	3910 ± 794a	0.8 ± 0.2	4372 ± 613a	1.5 ± 0.5	3988 ± 343a	7.1 ± 4.9
b. V16	3078 ± 257b	13.4 ± 4.1	2358 ± 280b	39.1 ± 9.6	2978 ± 303b	27.3 ± 6.3
c. R1	1259 ± 330c	27.6 ± 3.4	826 ± 437c	52.3 ± 8.1	1108 ± 344c	41.0 ± 5.7
$LSD_{0.05}$	149.4		128.9		105.8	

PP concentration of P in plant tissues; *PU* phosphorus uptake

[§] Means followed by the same letter(s) under each column and sub-heading are not significantly different from each other at $p \leq 0.05$

some significant implications with respect to P availability and mobility in Coastal Plain region.

Concentration of MEP in the soils (averaged across years) showed a declining trend from V6 to R1 stages of corn. Soil MEP decreased significantly from V6 (51.2 ± 30.6 mg kg^{-1}) to R1 (38.6 ± 16.1 mg kg^{-1}). Similarly, concentrations of MEP showed a decreasing trend from V6 to R1 among the different ST: (BnA 59.7–43.9 mg kg^{-1}; Dn 521–41.3 mg kg^{-1}; NcA 39.9–35.0 mg kg^{-1}; NkA 53.3–34.4 mg kg^{-1}) as shown in Fig. 4. The decreasing trends of MEP among the different ST from V6 to R1 can be further described by regression models shown in Fig. 4.

Water soluble P (WSP)

Like the concentration of MEP, concentration of WSP varied significantly ($p \leq 0.0001$) with Y, ST, CS and SD. However, concentration of WSP at all years (2013–2015) was not significantly affected by NM (Table 3). The greatest concentration of WSP in 2013, 2014 and 2015 was observed from BnA with mean values of 7.7 ± 3.1, 5.6 ± 2.6 and 5.7 ± 3.4 mg kg^{-1}, respectively (Table 3). The lowest concentration of WSP in 2013, 2014 and 2015 was from NcA with mean values of 3.4 ± 1.8, 3.4 ± 2.1 and 3.2 ± 2.4 mg kg^{-1}, respectively.

Similar to soil MEP, the upper soil depth (0–15 cm) when averaged across Y, ST and CS had the highest concentration of WSP (6.4 ± 2.9 mg kg^{-1}). The lowest concentration of WSP (3.3 ± 2.8 mg kg^{-1}) was found in the lower soil depth (15–30 cm). Result is suggesting that there will be about 50% less concentration of WSP in the lower soil depth and this may have had significant implication on P mobility and availability.

On the interaction effect of ST and CS, concentrations of WSP showed a decreasing trend from V6 to

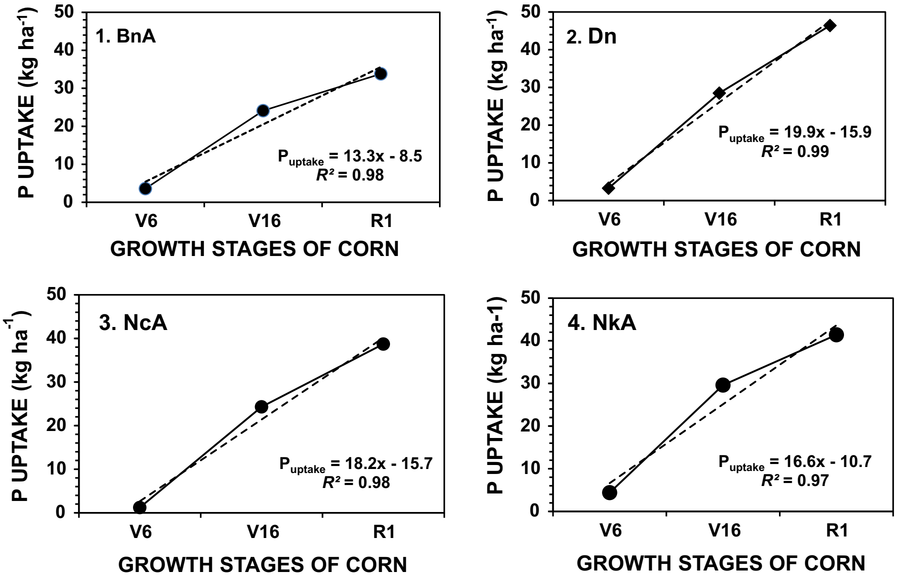

Fig. 3 Regression analyses of phosphorus uptake and growth stages (V6—early vegetative stage with 6 leaves; V16—late vegetative stage with 16 leaves; R1—silking stage) of corn from four different soil types

R1 among the different ST (Fig. 4). Concentrations of WSP from V6 to R1 among the different ST are as follows: BnA 7.8–5.1 mg kg^{-1}; Dn 5.2–4.4 mg kg^{-1}; NcA 3.6–3.3 mg kg^{-1}; NkA 8.2–3.8 mg kg^{-1}). Using regression analysis, NkA (−1.35 mg kg^{-1}) had the highest change in the concentration of WSP from V6 to R1 followed by BnA (−1.2 mg kg^{-1}), Dn (−0.4 mg kg^{-1}) and NcA (−0.2 mg kg^{-1}). The decreasing trends of WSP among the different ST from V6 to R1 can be further described by regression models shown in Fig. 4.

Table 4 showed the annual ratio of WSP and MEP and degree of P saturation (DPS) for the different ST as well as the 3-year average of WSP/MEP ratio and the DPS. Degree of P saturation or DPS is defined in Eq. 2 below (Sigua et al. 2013; Hooda et al. 2000).

$$\mathrm{DPS}\ (\%) = ([\mathrm{P}] \times 100)/[\mathrm{Fe} + \mathrm{Al}] \qquad (2)$$

where DPS is the degree of P saturation in %; [P] is the concentration of either WSP or MEP in mg kg^{-1}; [Fe] is the concentration of water-soluble or exchangeable Fe in mg kg^{-1}; and [Al] is the concentration of water-soluble or exchangeable Al in mg kg^{-1}.

Both the WSP/MEP ratio and the DPS varied significantly ($p \leq 0.001$) with ST. The greatest DPS was from NkA (20.0%) while the lowest average DPS was form NcA (9.6%). For the average WSP/MEP ratio, BnA had the greatest ratio (7.0) followed by NkA (4.6), Dn (4.3) and NcA (3.9).

Concentration of P in pore water

Table 5 shows the concentration of P in pore water from 2013 to 2015 as affected by ST, IS and NM at various CS. Figure 5 shows the concentration of P in pore water for irrigation scheduling (IPRO, NDVI and SWP) among the different ST. Concentration of P in pore water when averaged across years revealed that NcA (0.329 ± 0.293 mg L^{-1}) had the greatest concentration followed by BnA (0.296 ± 0.139 mg L^{-1}), Dn (0.268 ± 0.115 mg L^{-1}) and NkA (0.259 ± 0.069 mg L^{-1}). Annually, concentrations of P in pore water followed the trend of P in pore water as shown above (averaged across 2013–2015). For 2014 and 2015, the order of P concentration in pore water is as follows: NcA > BnA > Dn > NkA.

Concentration of P in pore water differed significantly ($p \leq 0.05$) with IS in 2014 and 2015, but not in 2013 (Table 5). In 2014, NDVI (0.361 ± 0.325 mg L^{-1}) had the greatest concentration of P while concentrations of P in pore water from IPro (0.284 ± 0.127 mg L^{-1}) and SWP (0.267 ± 0.105 mg L^{-1}) were statistically comparable. In 2015, SWP had the greatest concentration of P in pore water with a mean of 0.276 ± 0.125 mg L^{-1}

Table 3 Concentration of Mehlich extractable phosphorus (MEP), water-soluble phosphorus (WSP) and phosphatase enzyme in soils as affected by soil types, irrigation scheduling and nutrient management at various growth stages of corn

Treatments	Year 1 (2013)			Year 2 (2014)			Year 3 (2015)		
	MEP (mg kg^{-1})	WSP	Phosphatase (μg g^{-1} h^{-1})	MEP (mg kg^{-1})	WSP	Phosphatase (μg g^{-1} h^{-1})	MEP (mg kg^{-1})	WSP	Phosphatase (μg g^{-1} h^{-1})
1. Soil type									
a. BnA	70.2 ± 23.8a[§]	7.7 ± 3.1a	67.8 ± 23.0a	35.3 ± 12.9a	5.6 ± 2.6a	46.6 ± 24.8b	44.4 ± 13.7a	5.7 ± 3.4a	41.6 ± 25.0b
b. Dn	70.7 ± 30.3a	5.9 ± 2.8b	59.8 ± 24.8ab	32.9 ± 13.4ab	4.6 ± 3.7ab	54.7 ± 15.1a	35.2 ± 15.5b	3.7 ± 3.1b	56.2 ± 23.3a
c. NcA	51.1 ± 20.8b	3.4 ± 1.8c	56.8 ± 26.2b	31.5 ± 11.8ab	3.4 ± 2.1b	51.9 ± 19.2ab	28.1 ± 12.4b	3.2 ± 2.4b	60.8 ± 22.8a
d. NkA	54.3 ± 26.1b	7.1 ± 4.2a	60.7 ± 19.9ab	28.3 ± 9.8b	4.7 ± 2.7ab	48.3 ± 22.4ab	45.2 ± 16.3a	5.6 ± 4.2a	41.5 ± 23.3a
LSD$_{0.05}$	7.1	0.9	9.2	5.9	1.4	7.8	7.9	1.9	8.8
2. Irrigation Sched									
a. IPro	64.3 ± 19.9a	5.8 ± 3.1a	59.4 ± 24.0a	33.9 ± 13.6a	5.2 ± 3.7a	51.7 ± 20.5a	36.6 ± 12.2a	3.9 ± 2.3a	49.5 ± 24.9a
b. NDVI	62.6 ± 31.4ab	6.0 ± 3.3a	61.4 ± 24.6a	34.9 ± 11.6a	4.5 ± 2.4a	49.3 ± 20.6a	39.5 ± 18.2a	4.9 ± 3.9a	55.4 ± 25.0a
c. SWP	57.8 ± 27.9b	6.1 ± 3.9a	63.0 ± 22.8a	27.1 ± 9.9b	4.1 ± 2.4a	50.2 ± 21.4a	38.5 ± 17.4a	4.7 ± 3.9a	55.7 ± 23.5a
LSD$_{0.05}$	6.2	0.8	7.8	5.1	1.2	6.8	6.9	1.6	7.7
3. Nitrogen Mgt.									
a. 157 kg N ha^{-1}	62.6 ± 28.1a	6.0 ± 3.7a	68.7 ± 20.7a	32.4 ± 11.9a	4.4 ± 2.6a	61.7 ± 31.8a	37.6 ± 14.6a	4.6 ± 3.2a	67.5 ± 40.5a
b. 224 kg N ha^{-1}	60.6 ± 25.6a	5.9 ± 3.1a	67.1 ± 21.1a	31.7 ± 12.7a	4.2 ± 2.9a	64.9 ± 33.4a	36.3 ± 16.5a	4.3 ± 3.4a	76.3 ± 42.1a
LSD$_{0.05}$	8.8	1.2	6.9	3.5	0.8	9.3	4.4	0.9	11.8
4. Soil depth									
a. 0–15 cm	64.9 ± 26.2a	6.5 ± 3.2a	73.9 ± 17.4a	38.8 ± 12.1a	5.9 ± 2.3a	83.5 ± 32.2a	45.5 ± 15.8a	6.7 ± 3.2a	93.4 ± 42.7a
b. 15–30 cm	58.3 ± 27.2a	5.5 ± 3.6a	61.9 ± 22.3b	25.2 ± 7.9b	2.7 ± 2.3b	43.1 ± 16.4b	28.3 ± 9.2b	2.3 ± 1.4b	50.4 ± 26.4b
LSD$_{0.05}$	8.8	1.1	6.6	2.9	0.6	7.3	3.7	0.7	10.1
5. Corn Stage									
a. V6	82.9 ± 27.4a	8.2 ± 3.8a	63.4 ± 21.5a	33.2 ± 14.9a	5.8 ± 3.2a	36.9 ± 15.8b	37.7 ± 18.2a	4.6 ± 3.8a	57.8 ± 25.9a
b. V16	58.2 ± 16.4b	6.3 ± 2.3b	68.0 ± 22.7a	29.6 ± 9.1a	3.3 ± 1.5b	57.8 ± 20.4a	37.9 ± 15.1a	4.7 ± 3.6a	52.2 ± 24.8a
c. R1	43.6 ± 19.1c	3.4 ± 1.9c	52.3 ± 24.4b	33.3 ± 11.7a	4.7 ± 3.2a	56.4 ± 19.2a	39.1 ± 15.1a	4.4 ± 2.9a	50.5 ± 22.4a
LSD$_{0.05}$	6.2	0.8	7.8	5.1	1.2	6.7	6.9	1.6	7.6

[§] Means followed by the same letter(s) under each column and sub-heading are not significantly different from each other at $p \leq 0.05$

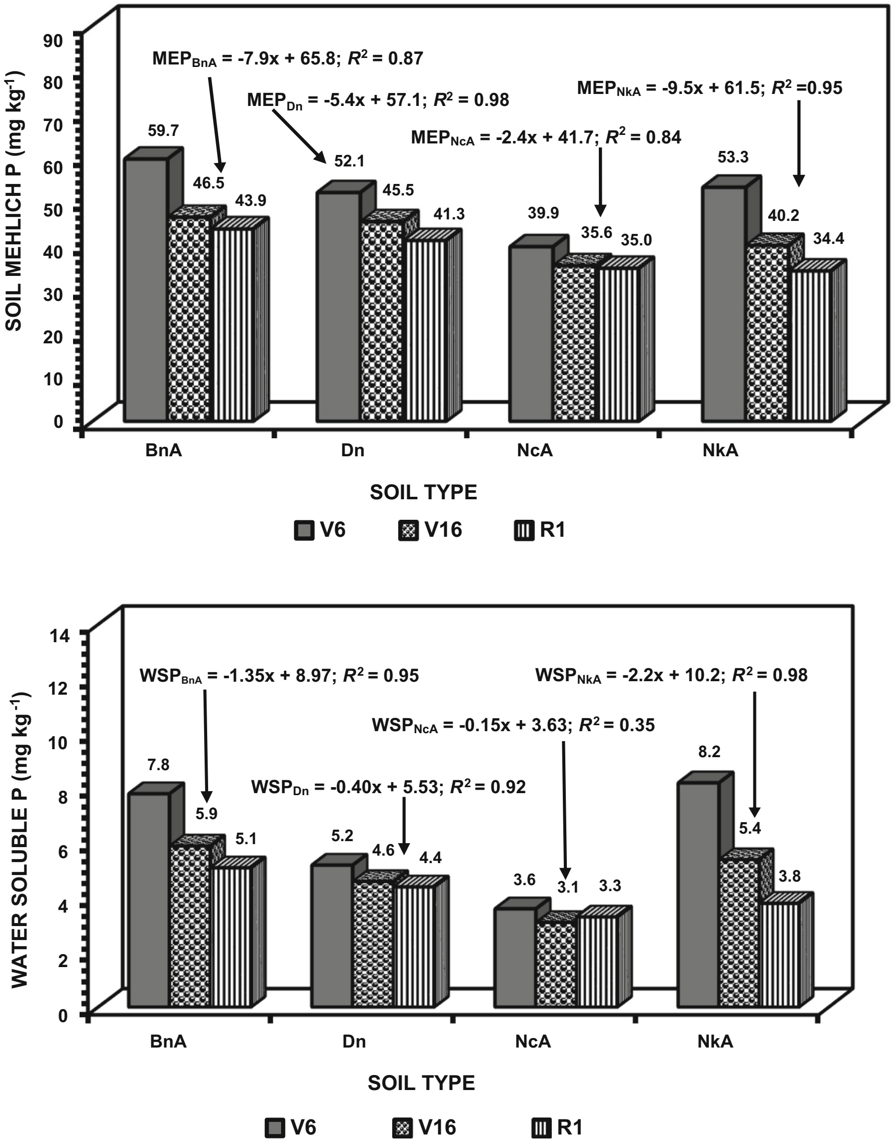

Fig. 4 Mehlich extractable phosphorus (MEP) and water soluble phosphorus WSP in four soil types (BnA—Bonneau; Dn—Dunbar; NcA—Noboco; NkA—Norfolk) and regression models describing the relationships of MEP and WSP with growth stages of corn in four soil types (x represents the actual number days after emergence (DAE) for each growth stage; i.e., V6—14 DAE; V16—56 DAE; R1—68 DAE)

while the lowest concentration of P in pore water was from IPro with mean value of 0.250 ± 0.001 mg L^{-1} (Table 5). Figure 5 shows the concentration of P in pore water as affected by IS among the different ST. The order of the concentrations of P in pore water (averaged across ST) from 2013 to 2015 is as follows: 2013 (IPro < NDVI < SWP); 2014 (IPro < SWP < NDVI); and 2015 (IPro < NDVI < SWP).

The effect of CS on the concentration of P in pore water was not as pronounced as in the concentrations of MEP and WSP in the soil. A variable trend on the effect of CS on P in pore water was observed among the different ST (Fig. 5). There was a slight increase in the concentration of P in pore water from V6 to R1 for BnA while concentration of P in pore water in Dn was not change. The concentration of P in pore water of NcA showed an increase of about 0.06 mg L^{-1}

Table 4 Ratio of water soluble phosphorus (WSP) to Mehlich extractable phosphorus (MEP) and degree of phosphorus saturation in soils under corn production (2013–2015)

Soil type	Year 1 (2013)	Year 2 (2014)	Year 3 (2015)	Average
WSP/MEP ratio				
BnA	9.8	4.9	6.2	7.0
Dn	6.5	3.0	3.2	4.3
NcA	5.4	3.3	2.9	3.9
NkA	5.8	3.0	4.8	4.6
Degree of P saturation, DPS (%)				
BnA	10.9	15.9	12.8	13.2
Dn	8.3	13.9	10.5	10.9
NcA	6.6	10.8	11.4	9.6
NkA	13.1	34.6	12.4	20.0

Table 5 Concentration of phosphorus in pore water as affected by soil types and different irrigation scheduling method at various growth stages of corn (2013–2015)

Treatments	Year 1 (2013) (mg L^{-1})	Year 2 (2014)	Year 3 (2015)
1. Soil type			
a. BnA	0.332 ± 0.192a[§]	0.278 ± 0.094b	0.258 ± 0.031b
b. Dn	0.250 ± 0.001a	0.290 ± 0.174b	0.257 ± 0.028b
c. NcA	0.302 ± 0.268a	0.392 ± 0.381a	0.283 ± 0.141a
d. NkA	0.251 ± 0.004a	0.272 ± 0.113b	0.250 ± 0.001b
$LSD_{0.05}$	0.08	0.07	0.01
2. Irrigation Sched			
a. IPro	0.285 ± 0.229a	0.284 ± 0.127b	0.250 ± 0.001c
b. NDVI	0.257 ± 0.037a	0.361 ± 0.325a	0.261 ± 0.036b
c. SWP	0.311 ± 0.171a	0.267 ± 0.105b	0.276 ± 0.125a
$LSD_{0.05}$	0.08	0.06	0.01
3. Nitrogen Mgt.			
a. 157 kg N ha^{-1}	0.292 ± 0.199a	0.296 ± 0.174a	0.253 ± 0.019a
b. 224 kg N ha^{-1}	0.277 ± 0.128a	0.312 ± 0.251a	0.271 ± 0.103a
$LSD_{0.05}$	0.06	0.07	0.03
4. Corn stage			
a. V6	0.265 ± 0.063a	0.298 ± 0.270a	0.256 ± 0.250b
b. V16	0.275 ± 0.129a	0.306 ± 0.183a	0.252 ± 0.017b
c. R1	0.319 ± 0.264a	0.309 ± 0.179a	0.282 ± 0.127a
$LSD_{0.05}$	0.08	0.06	0.009

[§] Mean s followed by the same letter(s) under each column and sub-heading are not significantly different from each other at $p \leq 0.05$

between V6 to R1 while a decrease of about 0.02 mg L^{-1} of P was observed between V6 to R1 in NkA (Fig. 5).

Concentration of P enzyme (phosphatase)

Concentration of phosphatase activity varied significantly with ST ($p \leq 0.0001$), CS ($p \leq 0.001$) and SD ($p \leq 0.0001$), but not with IS and NM (Table 3). In 2013, the greatest concentration of phosphatase was from BnA (67.7 ± 23.0 µg g^{-1} h^{-1}), Dn (54.7 ± 15.1 µg g^{-1} h^{-1}) in 2014 and NcA (60.8 ± 22.8 µg g^{-1} h^{-1}) in 2015 (Table 3). The lowest concentrations of phosphatase were observed from NcA (56.8 ± 26.2 µg g^{-1} h^{-1}) in 2013, BnA (46.6 ± 24.8 µg g^{-1} h^{-1}) in 2014 and BnA (41.5 ± 25.0 µg g^{-1} h^{-1}) in 2015.

While concentration of phosphatase activity was not affected by IS and NM, phosphatase concentration was significantly affected by depth of sampling.

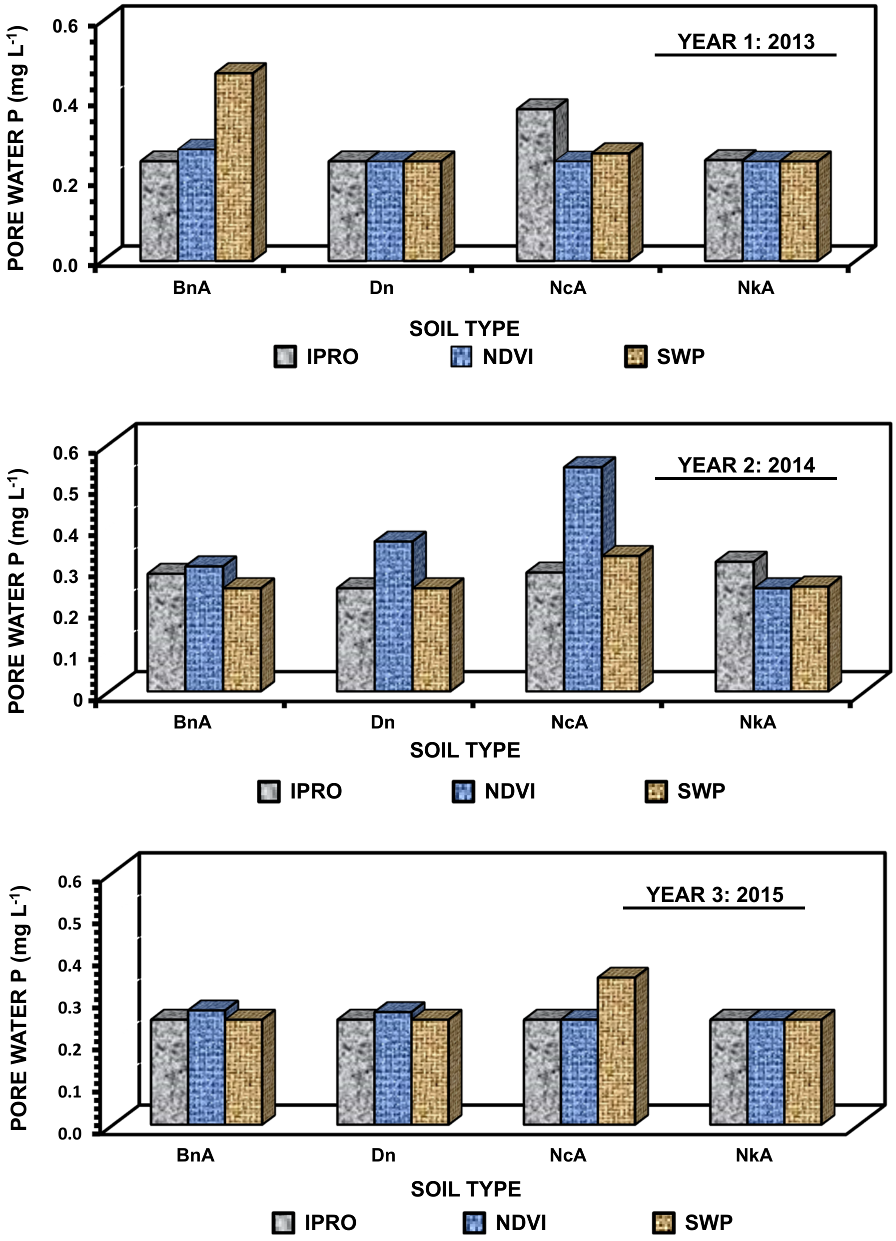

Fig. 5 Concentration of pore water phosphorus in four soil types (BnA—Bonneau; Dn—Dunbar; NcA–Noboco; NkA—Norfolk) as affected by irrigation scheduling from 2013 to 2015

Concentration of phosphatase activity in the upper soil depth (0–15 cm) with mean value of 62.3 ± 22.5 μg g^{-1} h^{-1} was significantly ($p \leq 0.05$) higher than the concentration of phosphatase activity in the lower soil depth (15–30 cm) with mean value of 47.7 ± 22.0 μg g^{-1} h^{-1} (Table 3). The difference in phosphatase concentration between the upper and lower soil horizons when averaged across Y and ST was about 14.5 μg g^{-1} h^{-1}.

The concentration of phosphatase activity in BnA when averaged across Y and SI was increased from 45.9 to 56.0 μg g^{-1} h^{-1} between V6 and V16, followed by slight decrease of phosphatase activity at R1 (54.0 μg g^{-1} h^{-1}) growth stage of corn. Concentration of phosphatase activity in Dn soil had decreased from 59.2 to 55.6 μg g^{-1} h^{-1} between V6 and R1. The concentration of phosphatase activity in NcA at V6 was about 57.0, 60.2 μg g^{-1} h^{-1} at V16 and 52.5 μg g^{-1} h^{-1} at R1. Similarly, concentration of phosphatase activity in NkA had increased from 48.8 μg g^{-1} h^{-1} at V6 to 65.5 μg g^{-1} h^{-1} at V16 and decreased to about 50.3 μg g^{-1} h^{-1} at R1.

Discussion

Effects of soil types

Soils on which crops are grown greatly influence how irrigation water, nutrients and other agrochemicals should be managed to maximize the production while minimizing resource use and effects on the environment (Sigua et al. 2010, 2011; Sato and Morgan 2012). Our results have shown broad effects of ST on variability of P dynamics and phosphatase activity in Coastal Plain soils under corn production. Concentrations of P in corn tissues, pore water, PU, MEP and WSP in our study varied significantly ($p \leq 0.0001$) with ST. This suggests that the effect of ST on P transformation and phosphatase activities could be important in monitoring the temporal and spatial changes in various fractions of soil phosphorus and for understanding the phosphorus cycling and dynamics.

Phosphorus dynamics in the soil and the ability of soil P renewal are essential pathways in the process of nutrient acquisition by plant roots (Bahl and Singh 1986). This ability of the soil to renew the P depleted by the plants is related to its capacity factor (Dalal and Hallsworth 1976). Again, differences in physical and chemical properties of soils used in our study (Table 1) might have had played major roles for the variable results of WSP, MEP and P uptake. The rate of P diffusion in our soils may vary significantly because of varying amount of clay contents, pH and fertility level. The rate of ion diffusion in soils is governed by factors like bulk density, cross-sectional area, tortuosity of the diffusion path and several physical and chemical phenomena occurring in soils (Hira and Singh 1977). Previous studies have indicated that diffusion of P in soil is influenced by the P adsorption characteristics (Vig and Dev 1979; Bahl and Singh 1986), water content and bulk density of the soil (Mathab et al. 1971). Sharpley et al. (1992) found the water soluble P transport depended on desorption-dissolution reaction controlling P release, which is consistent with our data. Since the process of adsorption, release and movement of P occur in the soil simultaneously; their dependence on ST and other edapahic factors like soil moisture are quite important (Bahl and Singh 1986).

Some important relationships that were reported by Porter et al. (1960) between P diffusion and soil properties that vary with texture were consistent with our data. We have shown the significant interactions effects among ST, IS and CS on P uptake and MEP. The data of Porter et al. (1960) at moisture contents from 1/3 to 15 bars tension show that the transmission or tortuosity factor $(L/L^e)^2$, is smaller for coarse-textured than for fine textured soil at any given moisture tension. Our results have shown that Dn soils with 169 g kg^{-1} clay content had the greater concentration of MEP (54.5 mg kg^{-1}) and higher P uptake (17.2 kg ha^{-1}) than the concentration of MEP (28.6 mg kg^{-1}) and P uptake (10.4 kg ha^{-1}) in NcA with clay content of 26 g kg^{-1}.

Differences in physical and chemical properties of soils used in our study (Table 1) might have had played major roles for the variable results of MEP and P uptake. Differences in the diffusion coefficients of P between sandy and clayey soils were considered to explain variations in rates of P uptake by corn seedlings from equal initial concentrations of P in the soil solution (Olsen and Watanabe 1963). Our results have shown that Dn soils with 169 g kg^{-1} clay content had the greater concentration of MEP (54.5 mg kg^{-1}) and higher P uptake (17.2 kg ha^{-1}) than the concentration of MEP (28.6 mg kg^{-1}) and PU (10.4 kg ha^{-1}) in NcA with clay content of 26 g kg^{-1}. Our results were consistent with the early findings of Olsen and Watanabe (1963) and Stroira et al. (2007). Stroira et al. (2007) demonstrated from their field experiments and batch study that two grassland soils had very different abilities as regards both their short- and long-term P supply. Their data confirmed that both time and P concentration in solution effects on the dynamics of the gross transfer of P ions was at the soil-solution interface.

Significant differences in the amount of phosphatase activities (μg g^{-1} h^{-1}) among the different ST ($BnA = 52.1 \pm 24.5$; $Dn = 56.9 \pm 21.1$; $NcA = 56.5 \pm 27.1$; $NkA = 50.2 \pm 21.9$) in our study could be explained by varying amount of carbon and P in the soils (Table 1). In an investigation by Boyd and Mortland (1990), the activity of acid phosphatase was correlated positively with organic matter and total P content of the soils. Soil enzymes may also be associated with clay-organic matter complexes and soil humus. The possible mechanisms of the formation of humus-enzyme complexes may include their physical entrapment in humus or clay-humus particles, ionic bonding and covalent attachment of the enzyme to soil humic substance (Boyd and Mortland 1990). Soil phosphatase activity was also affected by soil moisture. Harrison (1981) and Herbien and Neal (1990) have emphasized the significance of soil moisture on phosphatase activity in the soil.

Effects of irrigation scheduling

Irrigation scheduling is the process used by irrigation system managers to determine the correct frequency and duration of watering. A simple goal of the ideal irrigation scheduling would be to increase crop production while minimizing water loss by deep percolation, runoff or evaporation. Efficient water use efficiency may promote an increase in fertilizer retention in the effective root zone. One of the most important irrigation factors is irrigation uniformity, which is how evenly water is distributed across the field. Non-uniform distribution of irrigation water may create over- and/or under irrigated areas which can lead to yield reduction due to excessive nutrient leaching or plant water stress (Sato and Morgan 2012).

Our 3-year field study was conducted to evaluate and compare the effects of three IS on P dynamics and phosphatase activities in four ST at various CS of corn. Interaction effects of ST × IS and ST × IS × CS yielded highly significant effects on concentration of P, P uptake and MEP, respectively. These results suggest that the effect of IS could had been affected by the interactions of other factors like the different ST and growth stages of corn as shown by the different interaction effects described above. Similarly, the interval between irrigations and the amount of water to apply depend on how much water is held in the root zone and how fast it can be used by crops could be determined by other factors like soil texture, soil structure, depth of effective root zone, types of crop grown and crop growth stages (Sigua et al. 2017).

Difference in the concentration of P in pore water among the different IS can be related to the total amount of water (rain + irrigation) received by the crops over the 3 years by irrigation treatment and ST as described in early paper published by Stone et al. (2016). Their 3-year mean irrigation and total water the crop received was significant, with IPRO requiring greater irrigation than NVDI and SWP. The lower concentration of P in pore water in IPRO treatment compared with SWP and NDVI can be explained by higher total water and irrigation water depths in IPRO treatment than the other irrigation treatments. The total water was 546 mm for IPRO, 522 mm for NDVI and 510 mm for SWP (Stone et al. 2016). As Sigua et al. (2017) surmised, IPRO having the greatest amount of total water delivered into our plots may have had provided higher diluting effect on the concentration of NO_3 and pore water P as it moves down the soil profile. Figure 5 shows the concentration of pore water P in four ST as affected by IS from 2013 to 2015.

Our results have shown that the greatest concentration of MEP and P uptake of corn with mean values of 54.5 mg kg^{-1} and 17.2 kg ha^{-1} were from Dn soil with NDVI scheduling, respectively. The lowest concentration of MEP (28.6 mg kg^{-1}) and P uptake (10.4 kg ha^{-1}) were both observed from NcA soil with NDVI. Variability of MEP and P uptake could be explained by the significant interaction effects of ST and IS that were consistent with early results reported by Mackay and Barber (1985). Phosphorus uptake of plant has been reported to increase with increasing moisture content during the initial soil-monocalcium phosphate reaction period. The increased uptake was believed to be the result of differences in reaction products which were formed in the soil at the various moisture levels during the initial reaction period (Mackay and Barber 1985). On the other hand, various reasons may be advanced to explain why uptake of P declines as moisture tension increases. Moisture films connecting the roots and soil particles (represented by four ST in our study) become thinner and the path length of ion movement increases as the moisture tension increases and these changes could reduce the rate of P distribution to the roots.

Average concentration of P in pore water varied significantly with Y × ST × IS. Our results have shown that in 2014 and 2015, the lowest concentrations of P in pore water were from IPro with mean values of 0.284 ± 0.127 and 0.250 ± 0.001 mg L^{-1}, respectively. In 2015, SWP had the greatest concentration of P in pore water with a mean of 0.276 ± 0.125 mg L^{-1} while the lowest concentration of P in pore water was from IPro with mean value of 0.250 ± 0.001 mg L^{-1}. The order of the concentrations of P in pore water when averaged across ST is as follows: 2013 (IPro = NDVI = SWP); 2014 (IPro = SWP < NDVI); and 2015 (IPro < NDVI < SWP). Our results have shown that the different IS had minimized pore water concentrations of P in soils under corn production in Coastal Plain region. Since IPro method resulted in lower pore water P concentrations, results indicate that this scheduling method may be a way to reduce nutrient losses to leaching on these Coastal Plains soils. Our results were consistent with the early findings of Sigua et al. (2016, 2017) on using IPro in minimizing the concentration of pore water nitrate.

Effects of nutrient management

Phosphorus dynamics and phosphatase activities of four ST in Coastal Plain region were not significantly affected by NM. Additionally, we did not observe any interaction effects among ST, IS and CS with NM on P dynamics and phosphatase activities at all years in our study. Our results were in agreement with Ajwa et al. (1999) and Dillard et al. (2015). Ajwa et al. (1999) observed that acid phosphatase activity was not significantly different in plots that had been amended with 0 and 100 kg N ha^{-1}. These authors reported further that there was no difference in acid phosphatase activity of either fertilized and unfertilized soils. Similarly, Dillard et al. (2015) from their work on the effects of nitrogen fertilization on soil nutrient concentration and phosphatase activity reported no significant effects of N fertilization on soil phosphatase activity and concentrations of water soluble P. Olander and Vitosek (2000) suggested that the reason of not observing any significant effect of N fertilization on phosphatase activity in soils could be mediated through direct use of N as a primary component of N-rich enzymes, indirectly through increased productivity and P demand in response to alleviation of N deficiency.

Our results suggest that addition of nitrogen fertilizer at the rates of 157 and 224 kg N ha^{-1} had negative feedbacks on phosphatase activity, which is strongly supported by the results reported by Olander and Vitosek (2000). If the levels of N are greater than some threshold level (> 100 kg N ha^{-1}), phosphatase activity could have a negative feedback and further additions of the nutrient may result in additional suppression of enzyme activity. Where N supply is low, additions of N may stimulate production of phosphatase because N is essential for enzyme synthesis (Olander and Vitosek 2000). Dick et al. (1988) found that N fertilization in agricultural systems increased acid phosphatase activity, but Clarholm (1993) found that N fertilization had no effect on phosphatase activity. Therefore, negative correlations between phosphatase activity and application of N in our study are consistent with mechanism where production or activity of the enzymes is regulated or eventually inhibited by the large supply of the nutrients from application of fertilizers (McCarthy et al. 1992; Dick et al. 1994; Sinsabaugh 1994).

Effects of stages of corn growth

Phosphorus dynamics and uptake of P by plant roots are both active processes in the soil that can be affected by stages of plant growth (i.e., seedlings to maturity). As water is taken up by plants at various stages of growth to support transpiration, P may be moved to the root surface through mass flow and could alter P dynamics in general. Overall, P dynamics and phosphatase activity varied significantly with CS. Phosphorus uptake of corn had an increase of about 1200% from V6 to R1. Concentrations of MEP and WSP in the soils (averaged across Y) showed a declining trend from V6 to R1 stages of corn. Soil MEP decreased significantly from V6 (51.2 ± 30.6 mg kg^{-1}) to R1 (38.6 ± 16.1 mg kg^{-1}). Concentration of WSP also decreased significantly from V6 (6.2 mg kg^{-1}) to R1 (4.2 mg kg^{-1}). The two main factors controlling the availability of soil P to plant roots are the concentration of phosphate ions in the soil solution and the ability of soil to replenish these ions when roots remove them. Root length and diameter and the efficiency of P uptake by the roots determine the rate and extent of P uptake (Syers et al. 2008).

Phosphorus uptake of corn in our study was consistent with the normal patterns of plant uptake. Nutrient uptake parallels plant vegetative growth (V1 to V16) in many ways. Corn in our study take up the majority of nutrients (685% increased) during the periods of vegetative growth (V6 3.1 kg ha^{-1}; V16 23.6 kg ha^{-1}) and translocate stored nutrients to developing grain during reproductive growth (silking or R1 stage). Nutrient uptake increases rapidly from 4 to 6 leaf stage (V4 to V6), just prior to tasseling, and then stays at high levels until after pollination. After pollination, nutrient uptake slows down. Plant uptake of P is governed by diffusive action of P in soils (Stroira et al. 2007). Plant roots absorb P ions in solution and P ions release from soil constituents. A consensus exists that the diffusive supply of P in the soil is the major mechanism governing P uptake of plants (Hinsinger 1998). Adequate nutrients early in the growing season are necessary to maximize yield and ensure that nitrogen and P are available for good grain or seed fill.

Summary and conclusion

A 3-year (2013–2015) field study was conducted to evaluate the effect of integrated nutrient management and three irrigation scheduling methods (IS): irrigator pro (IPro); normalized difference vegetative index (NDVI); and soil water potentials (SWP) on P dynamics and concentration of phosphatase activity in four Coastal Plains ST at various CS (V6, V16 and R1) of corn. The dynamics of applied P in soils and its cycling in agroecosystems are of increased interest due to its contribution to the current environmental, agronomic and economic issues on intensification of agricultural production. The following conclusions are drawn from this study:

1. Soil types have shown broad and significant effects on P dynamics and phosphatase activity in Coastal Plain soils under corn production. Concentrations of P in corn tissues and pore water, P uptake, MEP and WSP in our study varied significantly with ST. This suggests that the effect of ST on P transformation and phosphatase activities could be huge in monitoring the temporal and spatial changes in various fractions of soil P and for understanding the P cycling and dynamics;
2. Phosphorus concentrations in plants, soils, pore water, P uptake and phosphatase activity was not significantly affected by IS. However, the interaction effects of ST × IS and ST × IS × CS yielded highly significant effects on P uptake and MEP and P concentrations in corn plants. These results suggest that the effect of IS could had been affected by the interactions of other factors like the different ST and growth stages of corn;
3. Phosphorus dynamics and phosphatase activities of four ST in Coastal Plain region were not significantly affected by NM. Addition of nitrogen fertilizer at the rates of 157 and 224 kg N ha^{-1} had negative feedbacks on phosphatase activity. If the levels of N are greater than some threshold level ($>$ 100 kg N ha^{-1}), phosphatase activity could have a negative feedback and further additions of the nutrient may result in additional suppression of enzyme activity; and
4. Overall, P dynamics and phosphatase activity varied significantly with CS. Phosphorus uptake of corn had an increase of about 1200% from V6 to R1. Concentrations of MEP and WSP in the soils (averaged across year) showed a declining trend from V6 to R1 stages of corn. Soil MEP decreased significantly from V6 (51.2 ± 30.6 mg kg^{-1}) to R1 (38.6 ± 16.1 mg kg^{-1}). Concentration of WSP also decreased significantly from V6 (6.2 mg kg^{-1}) to R1 (4.2 mg kg^{-1}).

Overall, our results further suggest that understanding of P inputs and outputs which include P accumulation in soils and plants, as well as P losses is critical to determining the environmental balance and accountability of P in agricultural ecosystem. Clearly, soil P dynamics have agronomic and environmental importance that may impact the development of effective and sustainable management plans.

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