2019 Progress Report
Summary Sheet

Grantee Information

Project Title: Understanding mechanisms and processes of dissolved reactive phosphate (DRP) loss in Illinois tile-drained fields

Institution: University of Illinois

Primary Investigator: Yuji Arai

NREC Project # 2016-4-360347-203

Is your project on target from an IMPLEMENTATION standpoint? ☒ **Yes** ☐ **No**

If you answered "no" please explain:

Is your project on target from a BUDGET standpoint? ☒ **Yes** ☐ **No**

If you answered "no" please explain:

Based on what you know today, will you meet the objectives of your project on-time and on-budget? ☐ **Yes** ☒ **No**

If you answered "no" please explain: The overall project is progressing accordingly. No cost extension was granted to complete the remaining objectives 3 and 4. We hires a post doc to finish the remaining tasks. We will finish the project by Dec 2020.

Have you encountered any issues related to this project? ☐ **Yes** ☒ **No**

If you answered "yes" please explain:

Have you reached any conclusions related to this project that you would like to highlight? ☐ **Yes** ☒ **No**

If you answered "yes" please explain:

Have you completed any outreach activities related this project? Or do you have any activities planned? ☐ **Yes** ☒ **No**

If you answered "yes" please explain and provide details for any upcoming outreach:

Understanding Mechanisms and Processes of Dissolved Reactive Phosphate (DRP) Loss in Illinois Tile-Drained Fields

2019 Progress Report for our NREC project

Yuji Arai, Mark David, Jennifer M. Fraterrigo, and Lowell Gentry
University of Illinois at Urbana-Champaign

Synopsis

Phosphorus (P) loss from agricultural fields is a pervasive problem generally associated with overland runoff following extreme precipitation events. Phosphorus concentrations and loads are more than enough to lead to eutrophication and algal production in downstream water bodies. Without a crop yield response to P loss (i.e., importance of soil test P), economics alone will not solve this problem. Illinois has recently developed a nutrient loss reduction strategy that calls for 45% reductions in P from both point and non-point sources (Illinois Nutrient Loss Reduction Strategy, 2015). This will be a major challenge for Illinois, as well as other Midwestern states. Phosphorus loss has long been known to be transported primarily with sediment, although several researchers reported P loss (dominantly dissolved reactive P) via tile drainage (Gentry et al., 2007; Royer et al. 2006; Xue et al., 1998). This body of work has been acknowledged in a recent special issue in the Journal of Environmental Quality which recognizes that tile transport has been overlooked and is an important P transport pathway (King et al. 2015a; King et al, 2015b; Smith et al. 2015). However, it is not known how and when DRP is released in tile flow in relation to the landscape surface topography, the subsurface networks of solute transport and the depth sequence of soil properties. Our proposed study will help to fill some of those gaps. This study will improve our understanding of DRP loss from surface soils to tile systems and from tile-drained fields and watersheds using detailed geostatistical analysis of terrains, monitoring of seasonal tile flow and DRP, soil physiochemical analysis of surface and subsurface soils including soil test P. Growers should be able to better interpret the variability of soil test P through the understanding of temporal and spatial variability of DRP in tile systems.

Objectives

The overall goal of this project is to evaluate physicochemical factors (e.g., soil test P, landscape topography, infiltration rate, and soil chemistry) influencing the seasonal distribution and movement of DRP in tile drainage systems. We will more fully understand the fate of DRP in relation to soil test P in current P management systems at long term tile-drained experimental fields in Illinois.

The objectives are to:

1. fully understand tile DRP losses in relation to soil test P (i.e., labile P in surface soils) for fields in east-central Illinois under typical corn and soybean production;
2. assess tile DRP losses in relation to spatial variability (i.e., fine scale topography) across fields and landscapes;
3. determine the relationship between land surface topography and tile DRP losses, examining soil physical properties (e.g., infiltration rate, hydraulic conductivity, soil P extraction relevant to soil test P);

4. examine the processes responsible for seasonal DRP release to tile lines, including physicochemical properties (e.g., depth sequence distribution of DRP and agronomic P soil test P) of subsurface soils; and
5. include a final report at the conclusion of this project that will address each of the objectives stated above and evaluate both the yield response and the tile losses of DRP/changes in soil test P.

Site Information:

Site information is updated in Table 1.

Table 1. Farms in or near the Embarras River watershed that currently have tile monitoring by our team as part of other projects, and will be used in this study.

	Tile # and type	Tillage	Cropping	Drainage area
				Acres
Salt Fork Watershed				
Farm 1	3 patterned fields	chisel	corn/soybean and corn/corn, one with cover crop	20-60
Farm 2	2 patterned fields	no-till (25+ years)	corn/soybean	25-55
Farm 3	3 random drainage fields	no-till and strip till	corn and soybean	40-60
Embarras Watershed				
Farm 4	2 patterned fields	chisel	seed corn/soybean	15 each
Farm 5	4 patterned fields	chisel	corn/soybean	20-250
Farm 6	1 patterned field	chisel	corn/soybean	50
Farm 7	1 patterned field	chisel	corn/soybean/wheat	12
Lake Shelbyville Watershed				
Farm 8	6 patterned tiles	no-till and strip till	corn/soybean/wheat with cover crops	25-70

NREC Progress Report (May 2019-Jan 2020)

Yuji Arai, Mark David, Jennifer M. Fraterrigo, and Lowell Gentry

University of Illinois at Urbana-Champaign

We are making steady progress toward the project goal. We completed objective 1, nearly completed objective 2 and made a progress in objective 3&4 according to the timetable. The progress report is summarized below.

Synopsis

Phosphorus (P) loss from agricultural fields is a pervasive problem generally associated with overland runoff following extreme precipitation events. Phosphorus concentrations and loads are more than enough to lead to eutrophication and algal production in downstream water bodies. Without a crop yield response to P loss (i.e., importance of soil test P), economics alone will not solve this problem. Illinois has recently developed a nutrient loss reduction strategy that calls for 45% reductions in P from both point and non-point sources (Illinois Nutrient Loss Reduction Strategy, 2015). This will be a major challenge for Illinois, as well as other Midwestern states. Phosphorus loss has long been known to be transported primarily with sediment, although several researchers reported P loss (dominantly dissolved reactive P) via tile drainage (Gentry et al., 2007; Royer et al. 2006; Xue et al., 1998). This body of work has been acknowledged in a recent special issue in the Journal of Environmental Quality which recognizes that tile transport has been overlooked and is an important P transport pathway (King et al. 2015a; King et al, 2015b; Smith et al. 2015). However it is not known how and when DRP is released in tile flow in relation to the landscape surface topography, the subsurface networks of solute transport and the depth sequence of soil properties. Our proposed study will help to fill some of those gaps. This study will improve our understanding of DRP loss from surface soils to tile systems and from tile-drained fields and watersheds using detailed geostatistical analysis of terrains, monitoring of seasonal tile flow and DRP, soil physiochemical analysis of surface and subsurface soils including soil test P. Growers should be able to better interpret the variability of soil test P through the understanding of temporal and spatial variability of DRP in tile systems.

Objectives 1& 2:

As we reported in the last annual report, we assessed tile DRP losses in relation to spatial variability in Farm 9. We worked on the analysis of Soil Test P and establishing the relationship between landscape topography and tile lines for Farm 6 and 8. The following figure shows that correlation between the surface topography and P in lbs/acre in two farms. Except for Farm 8

East, there is a positive correlation between STP and the depression depth. We will complete the assessment of tile DRP losses in relation to spatial variability in Farm 6 and 8 this summer.

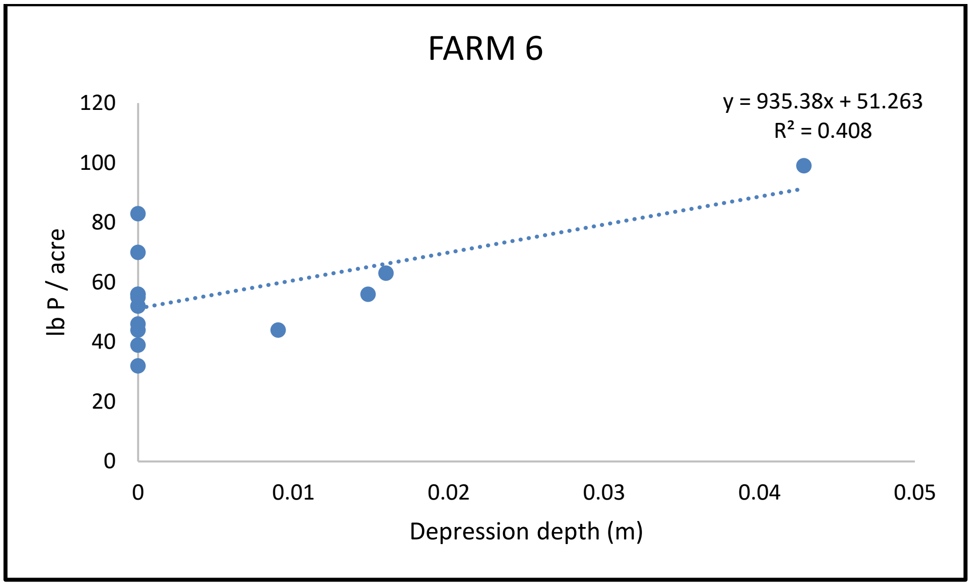

Figure 1: Relationship between depression depth and the results of soil test P in Farm 6.

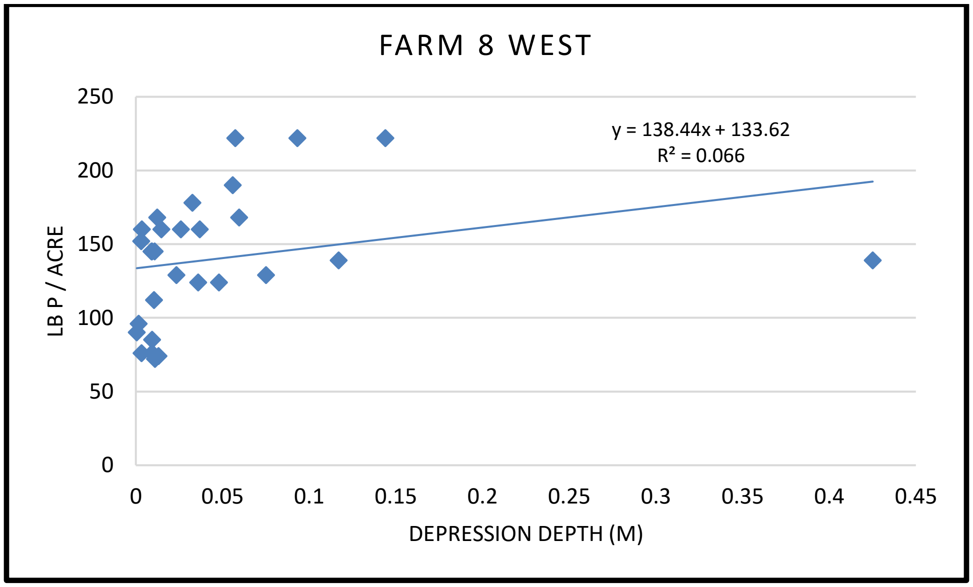

Figure 2: Relationship between depression depth and the results of soil test P in Farm 8 West.

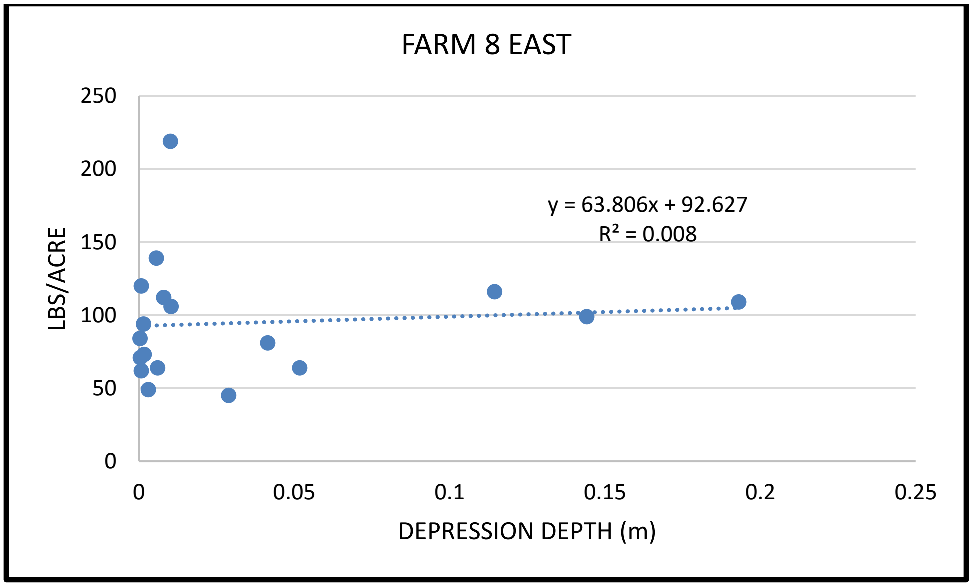

Figure 3: Relationship between depression depth and the results of soil test P in Farm 8 East.

We also conducted a detailed soil Bray P1 test (6 m grid) across the largest closed depression (near plot 4) in Farm 9/Douglas County. Piecewise regression revealed a critical threshold in the depression gradient at 0.38 m, at which soil P content abruptly shifted. Above this value, there was a strong positive association with soil P (R^2=0.91).

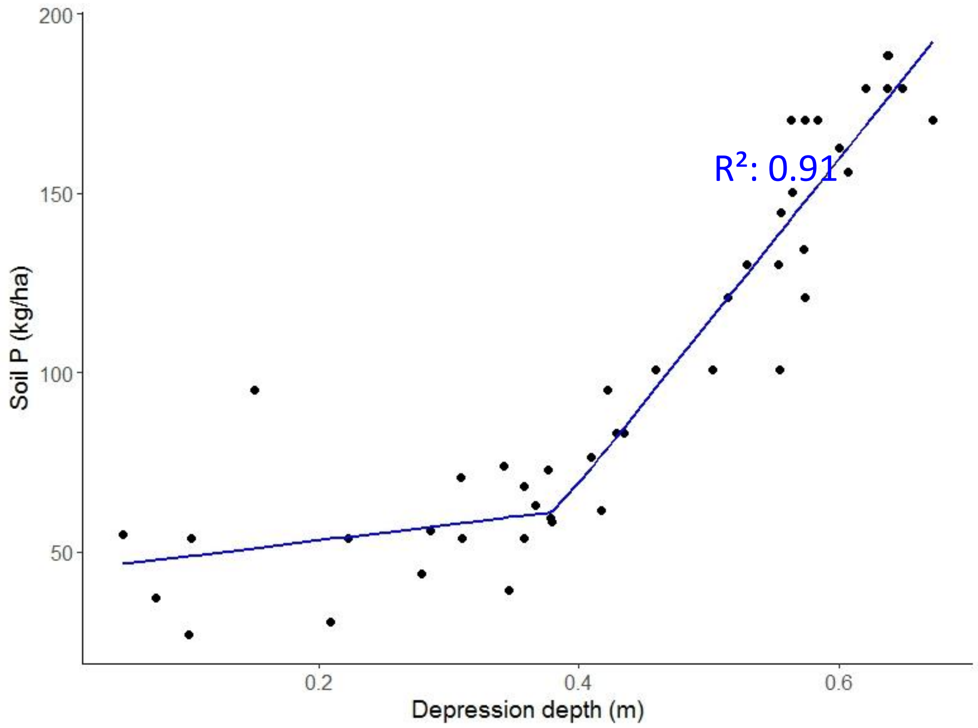

Figure 4: Piecewise linear regression between soil test P and depression depth in Farm 9.

Objective 2&3:

The objective 2 is to assess tile DRP losses in relation to spatial variability (i.e., fine scale topography) across fields and landscapes. After assessing the surface topography of farms that we originally proposed, we chose Farm 9 and 8 west for the assessment of tile DRP and the depression index.

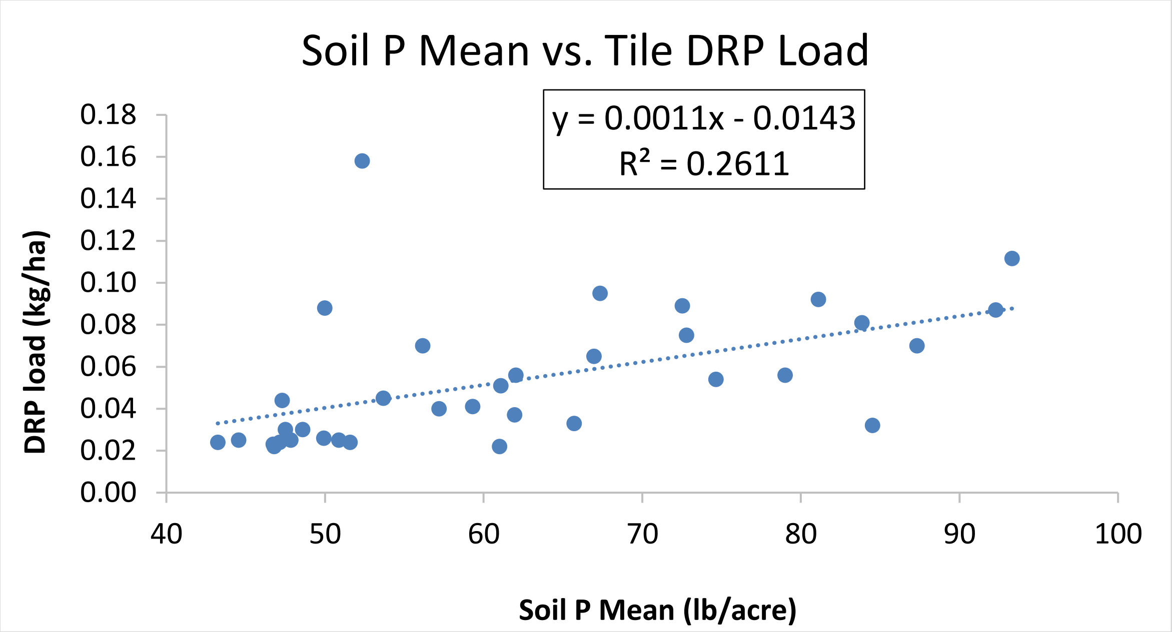

Figure 5. Regression of soil Bray P1 interpolated mean values and tile DRP load in 2016 for 36 tile laterals from Farm 9.

The R^2 value suggests there is a positive relationship between soil P and tile DRP load (Figure 5).

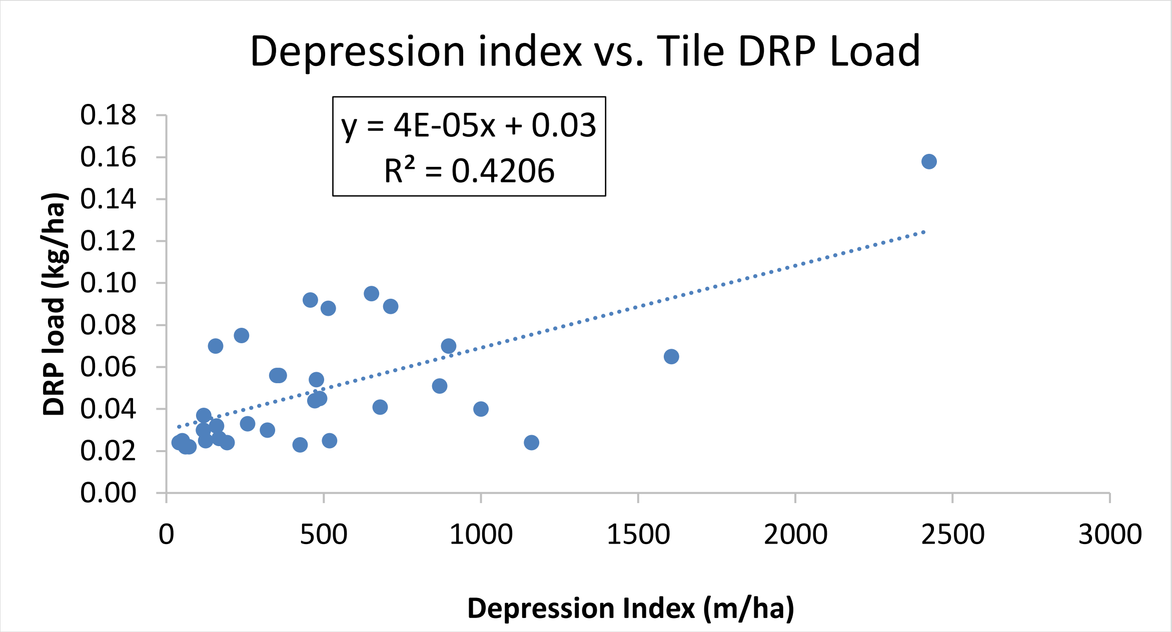

Figure 6. Regression of depression index values and tile DRP load in 2016 for 36 tile laterals from Farm 9.

The R^2 value suggests there is a positive relationship between depression index and tile DRP load, however, tile #4 (2425 m/ha; 0.158 kg/ha) is influencing the relationship (Figure 6).

For Farm8, we obtained the DRP data for the west part of the farm 8, which was the first one to be monitored. Preliminary flow data that do not account for by-pass flow in the AgriDrain structure of the woodchip bioreactors were used to estimate tile DRP yields and depression index/soil test P.

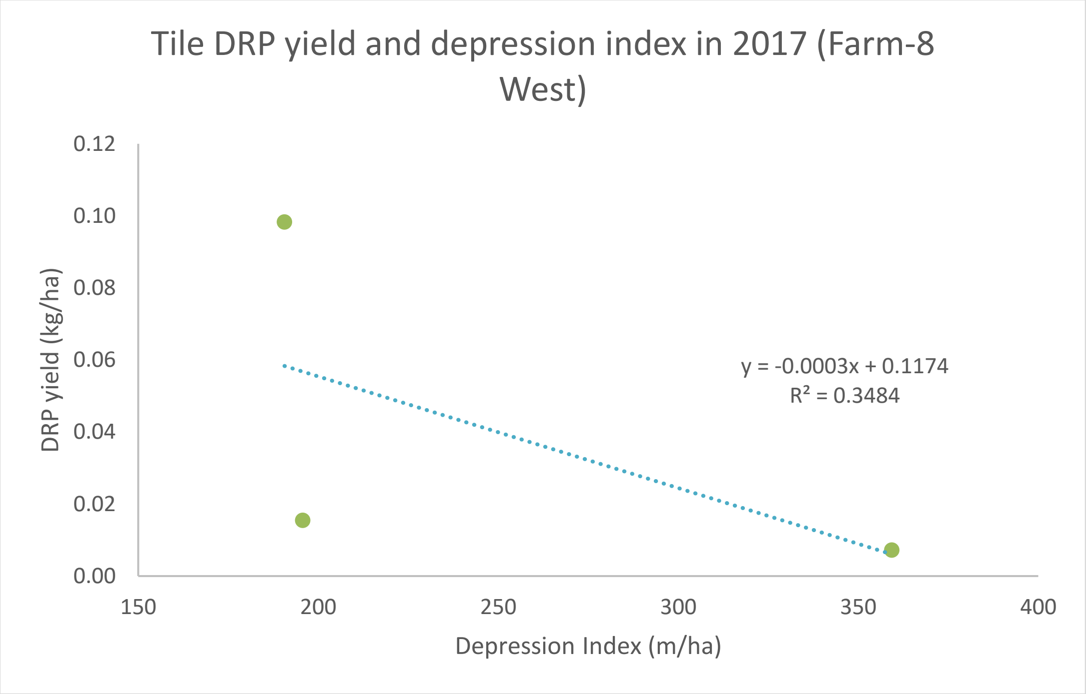

Figure 7. Regression of depression index values and tile DRP load in 2017 from Farm 8 west.

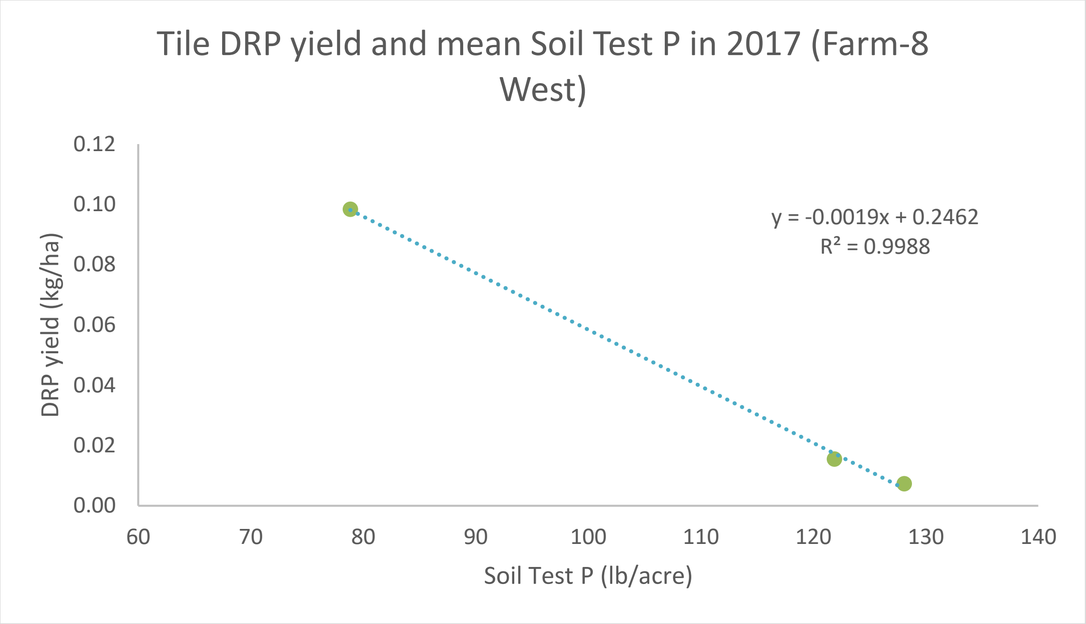

Figure 8. Regression of soil Bray P1 interpolated mean values and tile DRP load in 2017 from Farm 8 west.

While we observed correlation between tile DRP and depression index in Farm 9, we do not see any clear correlation between tile DRP and depression index in Farm 8 (Figure 7&8). The reason might be attributed to the acreage covered per tile line is much larger in Farm 8 than that in Farm 9. In Farm 8, various soil physicochemical management factors (till vs no-till) might be influencing the tile DRP loads.

Objectives 3 & 4:

We collected the additional saturated hydraulic conductivity (Ksat) measurements in Farm 9 in spring. The measurements of Ksat we completed in March 2018. Ninety nine STP sampling points in Farm 9 were used to compare with the Ksat data in 2017. Based on the previous year's measurements, we tested the hypothesis that crop specific roots system is driving the macropore structure in soils in soybean system. The Ksat measurements in two fields (previously corn and soybean were grown) are shown in Figures 9 and 10.

In the field with tile #4-#27 where corn was grown in the preivous year, average Ksat is 2.3E-03 cm/s (Figure 9). At the majority of sites, Ksat was greater than 0.001 cm/s (Figure 9). The average Ksat of the area (tile #28-48) is significantly lower, 8.03E-03 cm/s (Figure 10) than that in the soybean field. Although the data are variable (at only few locations), Ksat at most of sites are less than 0.001cm/s.

We conducted the statistical analysis to evaluate the effect of cropping system on Ksat. In this particular year, we did not clearly observe the impact of crop specific roots system on the hydraulic conductivity values. Instead, we observed the preferential flow in both corn and soybean field. The soybean field tends to exhibit a few extreme cases. Similar to the last year, we did not observe any correlation between STP and Ksat (Figures 11 and 12). This suggests that observed P accumulation was not affecting the drainage as the result of P induced colloidal dispersion.

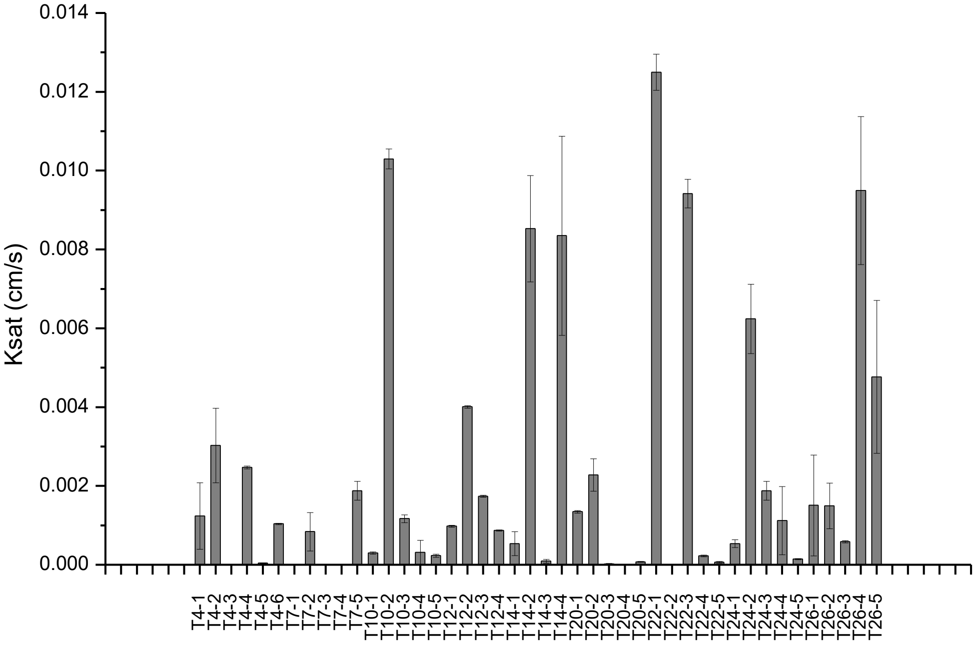

Fig 9. The results of saturated hydraulic conductivity measurement in Tile #4-Tile 26 where corn was grown in the previous year.

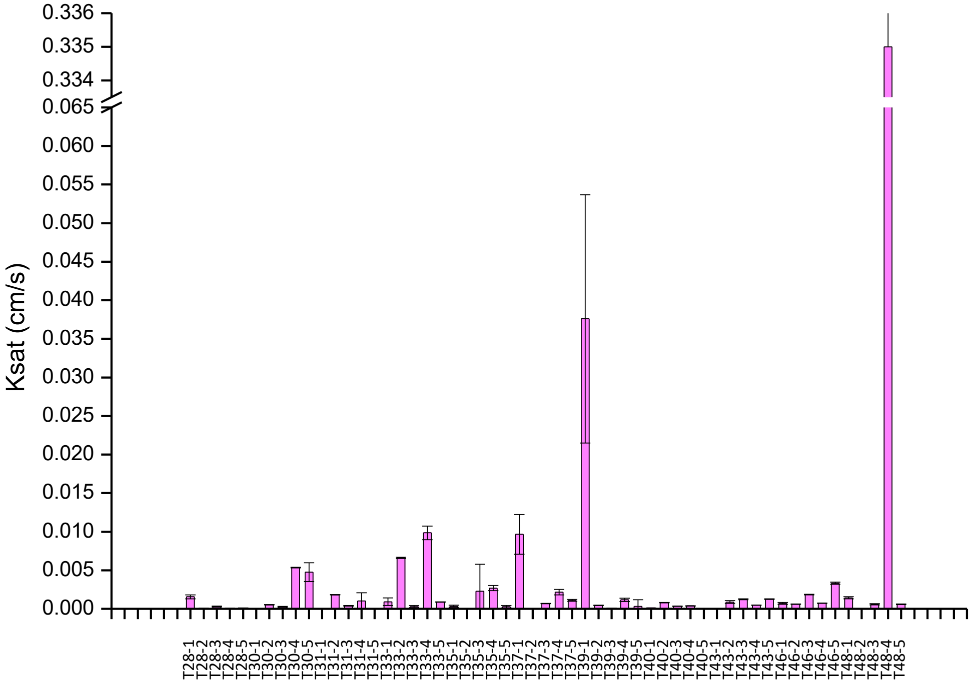

Fig 10. The results of saturated hydraulic conductivity measurement in Tile #28-Tile#48 where soybean was grown in the previous year.

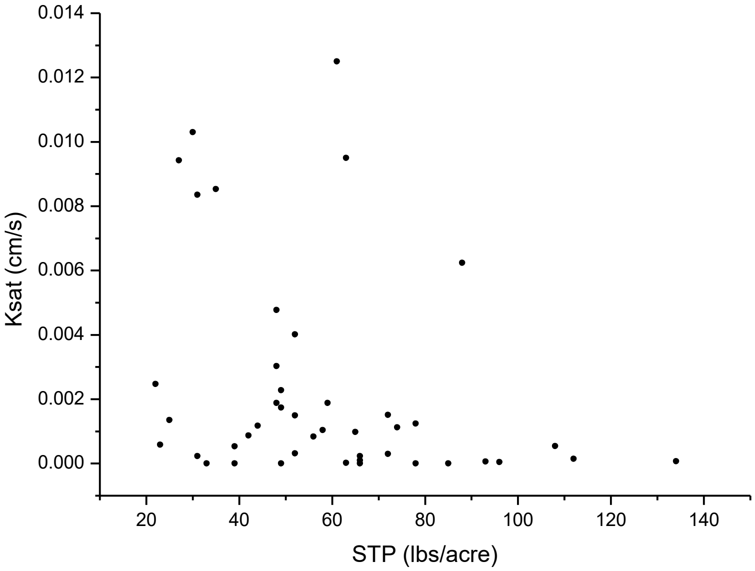

Fig 11. Correlation between STP and Ksat in Tiles #4- 27 where corn was grown in the previous year.

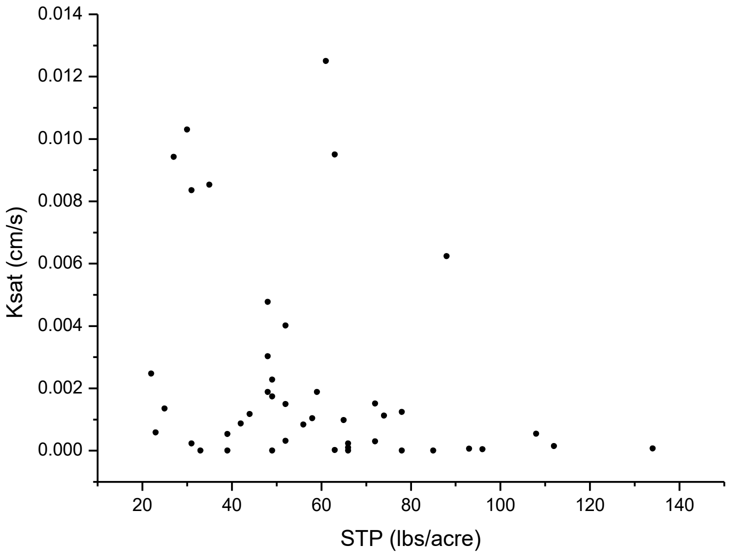

Fig 12. Correlation between STP and Ksat in Tiles #28- 48 where soybean was grown in the previous year

In this 2019 mid summer report, the results of physiochemical characteristics of soils, the depth sequence distribution of inorganic- and organic-P and reactivity in soil core samples from farm 8 are reported.

Physicochemical characterization of soils

The major soil series of S1-S2 and S3-S6 are Milford silty clay loam (0 to 2 % slopes, fine, mixed, superactive, mesic Typic Endoaquolls) and Drummer-Milford silty clay loams (0 to 2 % slopes, fine-silty, mixed, superactive, mesic Typic Endoaquolls), respectively. Throughout the rest of the discussion, surface and subsurface soils referred to the depth of 0-36cm and 37-180cm, respectively (Table-2).

Quartz and muscovite are dominant minerals in surface soils. Vermiculite, illite, kaolinite, chlorite, and albite were also found in most samples. S4 also contains dolomite. The subsoils consist of quartz, muscovite, vermiculite, chlorite illite, albite, and kaolinite. Dolomite and calcite were also found in the subsoils of in S1 and S2 and in the subsoils of S1-S2. Additionally, hematite in S1 surface soil. In most of the samples, the average % OC decreases from ~2.4% to ~0.5% with increasing depth (Table-2) while the average % IC increases from 0.1% to ~2.2% with increasing depth.

The overall trend of soil pH increases from moderately acid to alkaline with increasing depth in all soil cores. Organic acids in the surface soils buffer soil pH at mildly acidic pH (Guppy, Menzies, Moody, & Blamey, 2005). High base saturation (e.g., > 50 % of Ca) (Table-1) and carbonates and dolomite (see the XRD section below) in subsoils could alkaline soil pH (Amundson, Guo, & Gong, 2003; Rebsdorf, Thyssen, & Erlandsen, 1991; Rogovska, Blackmer, & Mallarino, 2007). Subsurface soils are generally at alkaline pH (> 7.3). The high (>90%) base saturation (e.g. Ca^{2+}, Mg^{2+}) in soils in Douglas County is associated with calcareous materials in subsoils such as dolomite (calcium-magnesium carbonates) and calcite (calcium carbonates) (MacCarthy, Malcolm, Clapp, & Bloom, 1990; USDA Soil Survey, 2006).

Cation exchange capacity for most soil samples is moderate to high (~21-32 $cmol_c/kg$) (Table-2). All CEC values are consistent with the soil survey report (USDA Soil Survey, 2006). The silty clay loam texture is contributing to the high CEC. The percent base saturation is very high (>80%) for most samples, and moderate to high (60-80%) for surface samples from S3-S6. The samples from S1and S2 have the highest % base saturation of all samples.

Mehlich III P (M3P) is high in the surface soils and decrease with increasing depth in all samples (Table-1). Overall, the extracted P concentration in S1and S2 is lower than that in S3-S6 at the respective depth. The M3P in surface soils is considered high (17-25 mg/kg) to moderate (10-17 mg/kg) in S1and S2 and very high (>25 mg/kg) in S3-S6, while the M3P for the subsoils is very low (<5 mg/kg) in all samples. According to the Illinois Agronomy Handbook (2008), P-supplying power in these soils is classified to medium, and the recommended soil P test value for corn and soybean growth in this region is about 45 lb/A (15-22.5 mg/kg) for surface soils (Fernández & Hoeft, 2008). The M3P of S3-6 top soils is ~31-65 mg/kg that is much greater than the recommended value, whereas the M3P of S1 and S2 in the surface horizon is within this range. This suggests that available P is sufficient in the surface soils (0-18 cm) for corn and soybean.

Total Inorganic and Total Organic P Fractionation

The results of total inorganic P (TIP), total organic P (TOP), and total P (TP) are summarized in Fig. 13. Total P is ranging from ~200 to ~450mg/kg in all soil scores. It generally decreases with increasing depth. Total inorganic P is the dominant P fraction in these soils. It accounts for ~51-77% of TP in surface soils and ~70-98% of TP in subsoils. The average TIP in soils from S1 and S2 (~284.40 mg/kg) is much greater than that in S3-S6 (~220 mg/kg). Total organic P is ~30-40% of TP in surface soils and is less than 10% of TP in subsoils. The average concentration of TOP (~68.06 mg/kg) in soils from S3 and S4 is much lower than that from S1 and S2, and S5 and S6 (~88 mg/kg). This is attributed to the cover crops at S3-4 provide sufficient OC in soils which facilitate the decomposition of OP. The concentration of TOP in the surface soils is ~70-150 mg/kg, which gradually decreases to ~10-40 mg/kg with increasing depth.

Inorganic P Fractionation

The results of operationally defined inorganic P fractions of soils are shown in Fig. 14. The contents of each inorganic P fractions are mainly in the order of calcium-P > non-occluded P > Fe occluded P > soluble P for surface soils, while the fractions of non-occluded P and Fe occluded P are similar but still significantly less than calcium-P in subsoils.

In all soil samples, the calcium-P fraction (Ca-P) is dominant (~42-97% of TIP). In each soil core, the Ca-P fraction is about 40-70% of TIP in the uppermost surface horizon (0-18 cm) which pronouncedly increases to ~80-97% of TIP in subsoils. The highest proportion of Ca-P is at the middle depth in most soil cores (90-108 cm for S1, S2, S5 or 144-162 cm for tile S6) except for the sample from S3 or S4. In these two soil cores, the Ca-P fraction increases with increasing depth and had the highest value at the depth of 162-180 cm.

The second largest inorganic P pool is in non-occluded P fraction (i.e. amorphous Fe-P) which is about 9-40% of TIP in surface soils and < 9% in subsoils. Generally, the amount of non-occluded P decreases with increasing depth. Compared to Fe occluded P, a higher fraction of non-occluded P is observed in surface soils except S1. For subsurface soils, these two fractions are not significantly different.

The bicarbonate-citrate-dithionate extractable P (Fe occluded P) concentration ranges from ~4 to 80 mg/kg (~4-30% of TIP) in all soils. In all soil cores, Fe occluded P fraction is about 6-30% of TIP in surface soils, and <10% of TIP in subsurface soils.

Soluble P generally accounts for ~ 1% of TIP. But the considerable amount is consistently observed in surface soils in all samples.

Organic P speciation

Solution ^{31}P-NMR spectra from selected soils from S1-S6 are shown (Fig. 15). Selected ranges of chemical shifts (8.0 ppm, -5.0 ppm) and peak assignments are included. The chemical shifts of orthophosphate, pyrophosphate and all monoester groups are according to the previous literature (Cade-Menun, 2015; Doolette et al., 2009; Z. He et al., 2011; Missong et al., 2016; Schneider et al., 2016; Turner, Mahieu, & Condron, 2003). The dominant peak in each NMR spectrum is orthophosphate (orthoP) at 6 ppm which occurs IP in soils. Peaks detected in the major OP compounds correspond to several P-monoesters (5.82-3.00 ppm). They are myo-Inositol hexakisphosphate (myo-IHP), myo-Inositol 1 dihydrogen phosphate (myo-IDHP), chiro-Inositol hexakisphosphate, 2equattorial/4 axial conformation (chiro-IHP (2e/4a)), glucose6-phosphate (G6-P), 3-sn phosphatidic acid (3-sn PA), α-glycerophosphate (α-gly), β-glycerophosphate (β-gly), mononucleotides (monoN), phosphocholine (Pchol), and scyllo-Inositol hexakisphosphate (scyllo-IHP).

The percent OP fraction decreases with increasing depth in S1 and S2. There are no major differences in the types of OP compound throughout the soil profile in S1-S4. The monoester group is dominated by IHP (including myo-IHP, chiro-IHP, and scyllo-IHP) followed by monoN, and other unidentified monoester group compounds. In S1 and S2, the P-monoester group mainly includes total IHP (2.30-22.80%), monoN (4.07-16.95%), α-gly (0-6.73%), β-gly (0-7.88%), and Pchol (0-8.25%). For tile line 37, the P-monoester group mainly includes total IHP (8.61-26.45%), monoN (6.75-16.95%), α-gly (0-4.31%), β-gly (0-10.6%), and Pchol (1.99-6.29%).

Phosphorus XANES Analysis

The results of XANES analysis of selected soil cores (S1 and S3) are shown in Fig. 16. The reduced chi of ≤0.005 indicated an excellent fit using several reference spectra (Table-3). The surface soils of S1 (0-36cm) contain phytic acid adsorbed ferrihydrite (~48-61%), phosphate adsorbed aluminum oxide and calcite (~23-38%). With increasing depth, P adsorbed calcite dominates (~68-91%) in S1 subsoils (S1_7 and S1_8) with ~30% hydroxyapatite in S1_8.

Similarly, surface soils in S3 (S3_1 and S3_2) contain phytic acid adsorbed ferrihydrite (~19-21%), phosphate adsorbed aluminum oxide and calcite (~21-33%), and some phytic acid adsorbed gibbsite/ calcite (~5-21%). In the subsurface soils (91-144cm) of S3_7 and S3_8, inorganic P species dominate. P adsorbed calcite (~67%), pyrophosphate (~2-3%), P adsorbed ferrihydrite (~6-9%) and hydroxyapatite (18-31%).

Long-term P Desorption

The results of long-term P desorption experiments are shown in Fig 5. The cumulative P desorbed is ~3-15 mg/kg after 30 days. Within each soil core, P desorbed from surface soils are significantly higher than that from subsurface soils. The total desorbed P generally decreases with increasing soil depth. In subsurface soils (>54 cm), the cumulative P desorbed (mg kg^{-1}) from different samples is not significantly different. The concentration is generally <1.0 mg kg^{-1}. The highest total P released is in S3 at a depth of 0-18 cm, and its cumulative P release is 17.28 mg kg^{-1}. Because the soil sample from S3 has the highest TIP value (Fig. 14) in surface soils, the result of desorption makes sense. The lowest cumulative desorbed P occurs in surface samples from S1which also has the lowest TIP value (Fig. 14) in surface soils. However, this trend with TIP is not observed in subsoils. This suggests that mechanisms of P release might not be concentration-dependent in subsoils.

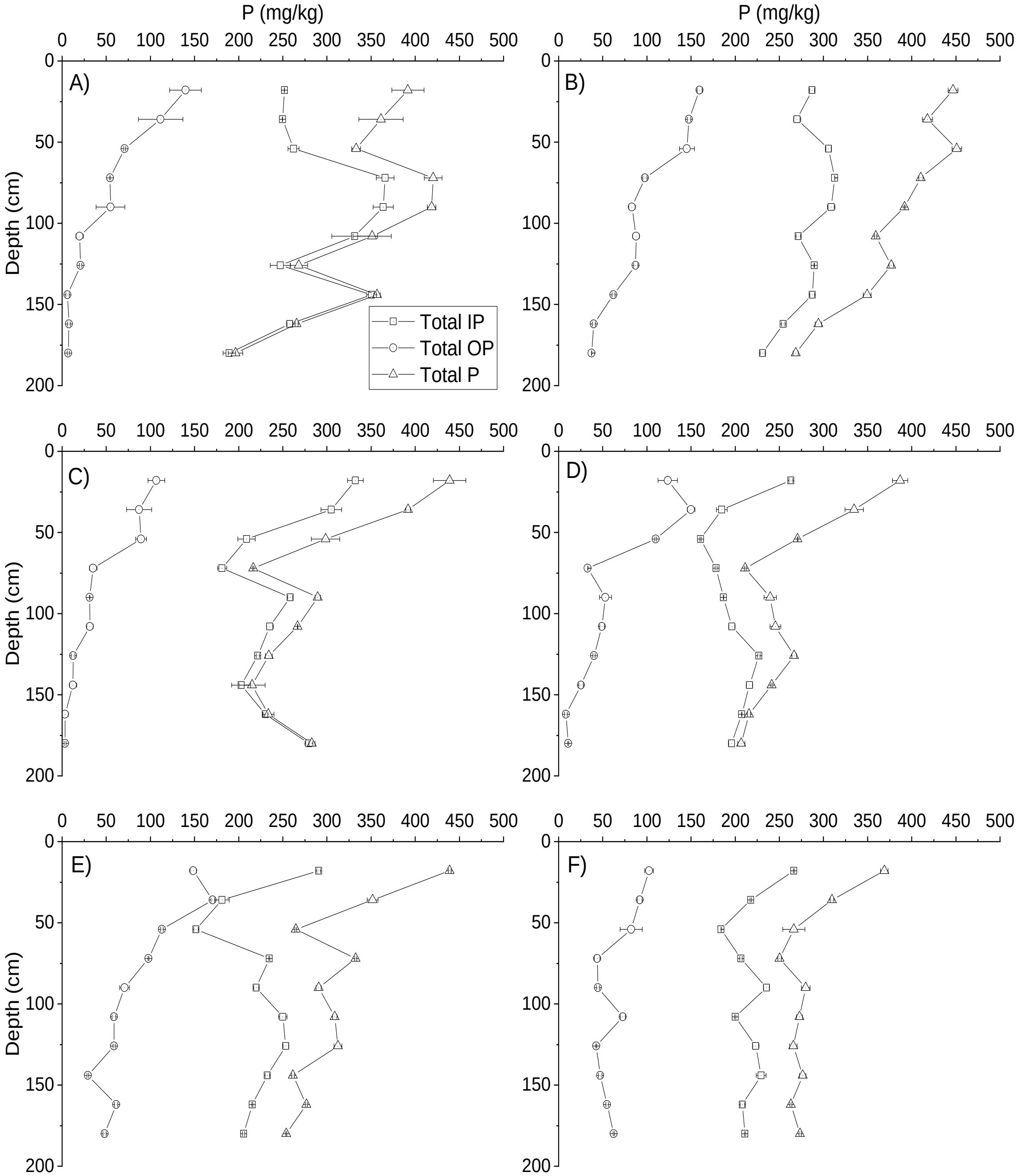

Fig. 13. Depth sequence distribution of total inorganic P, total organic P, and total P fraction in six soil core samples. A) soil core 1 (S1); B) soil core 2 (S2); C) soil core 3 (S3); D) soil core 4 (S4); E) soil core 5 (S5); F) soil core 6 (S6).

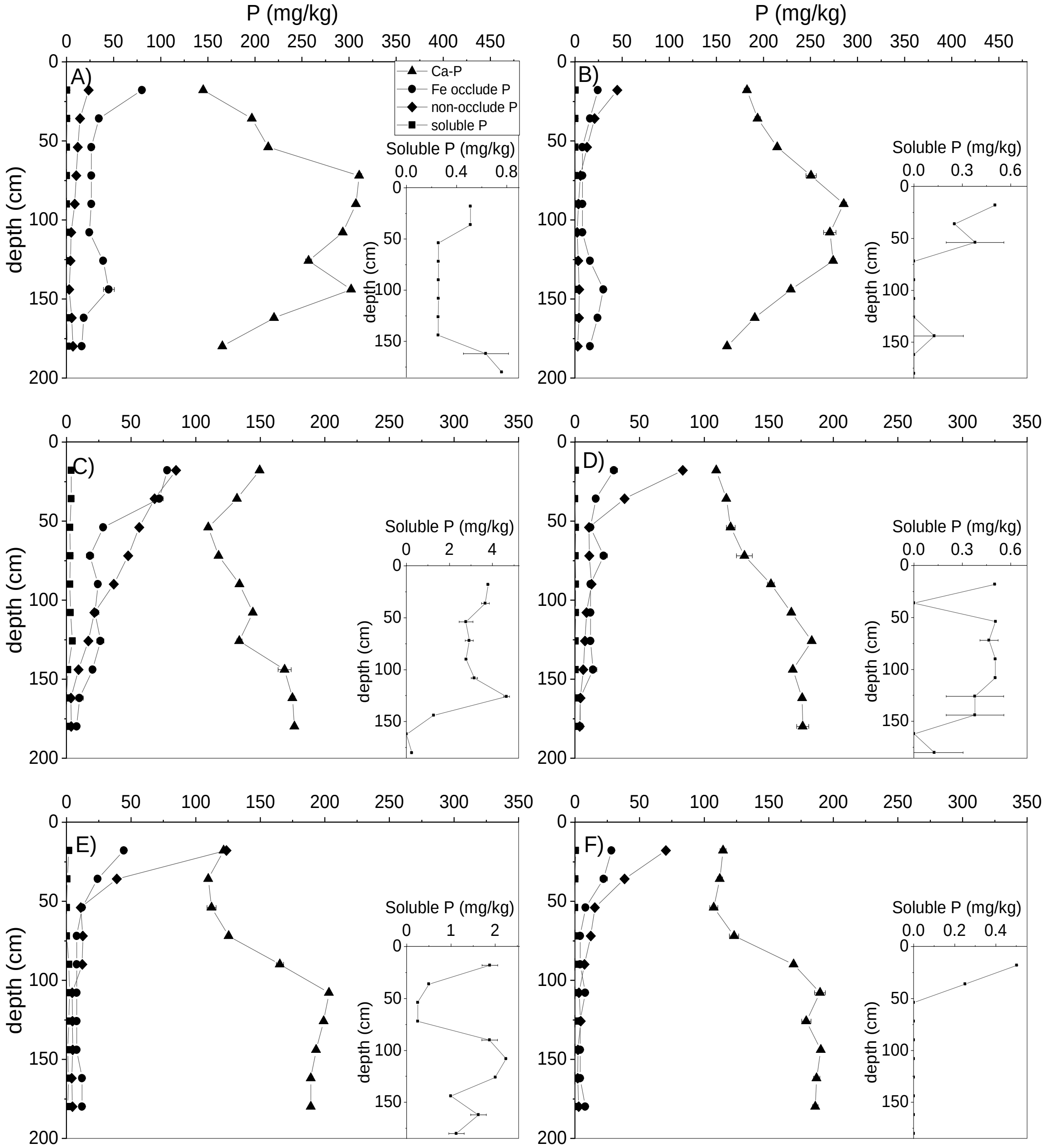

Fig. 14. Depth sequence distribution of inorganic P fractions in three soil core samples. A) soil core 1 (S1); B) soil core 2 (S2); C) soil core 3 (S3); D) soil core 4 (S4); E) soil core 5 (S5); F) soil core 6 (S6). Calcium associate P (Ca-P), Iron occluded phosphate fraction extracted by the sodium citrate-bicarbonate-dithionite (Fe-occluded P), the fraction extracted with 0.1 M NaOH and 1 M NaCl solution (non-occluded P), and the soluble P fraction extracted with 1.0 M NH_4Cl solution.

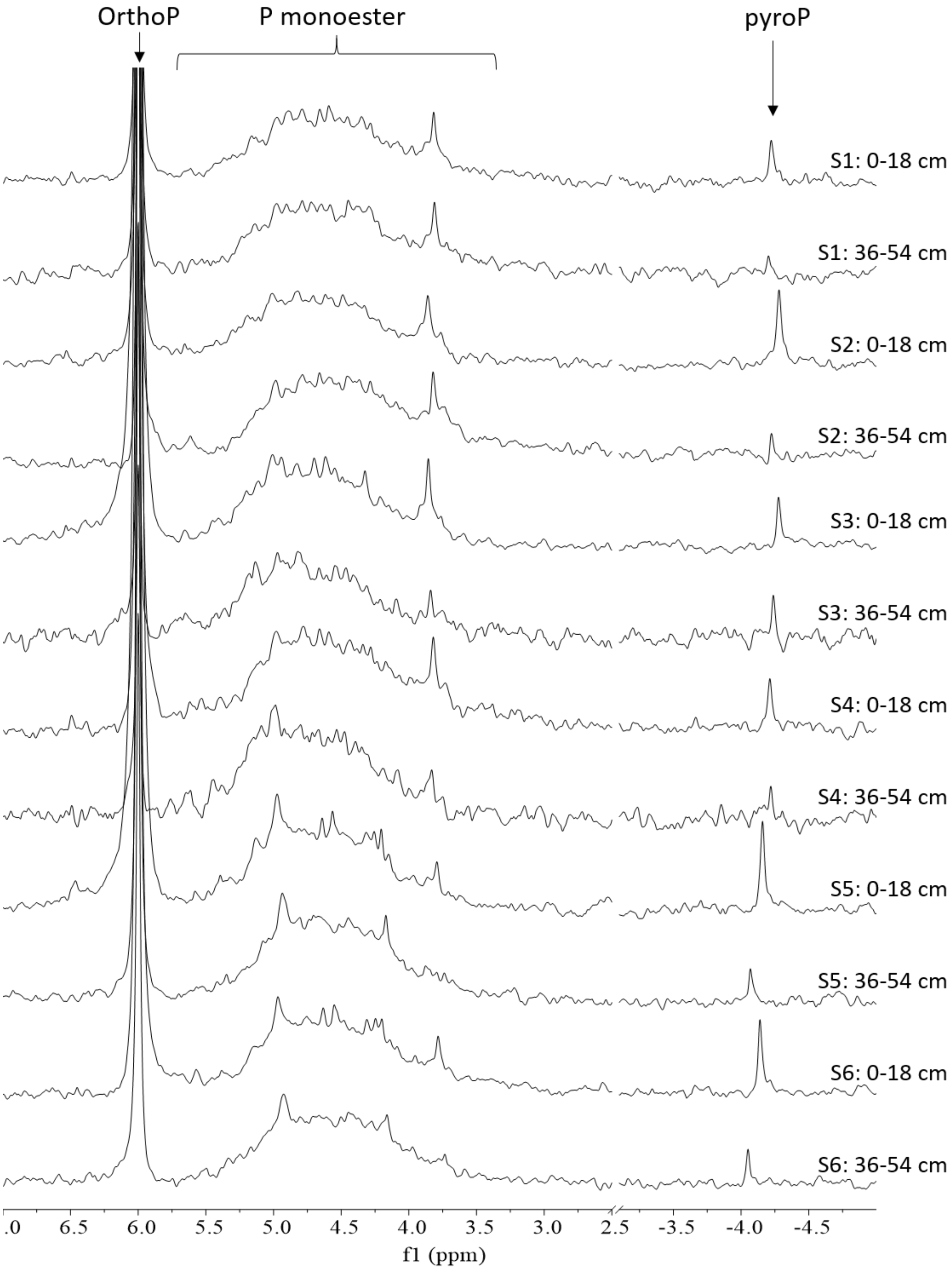

Fig. 15. Phosphorus-31 nuclear magnetic resonance spectroscopy (^{31}P-NMR) spectra of selected soil samples at depth of 0-18, 36-54 cm.

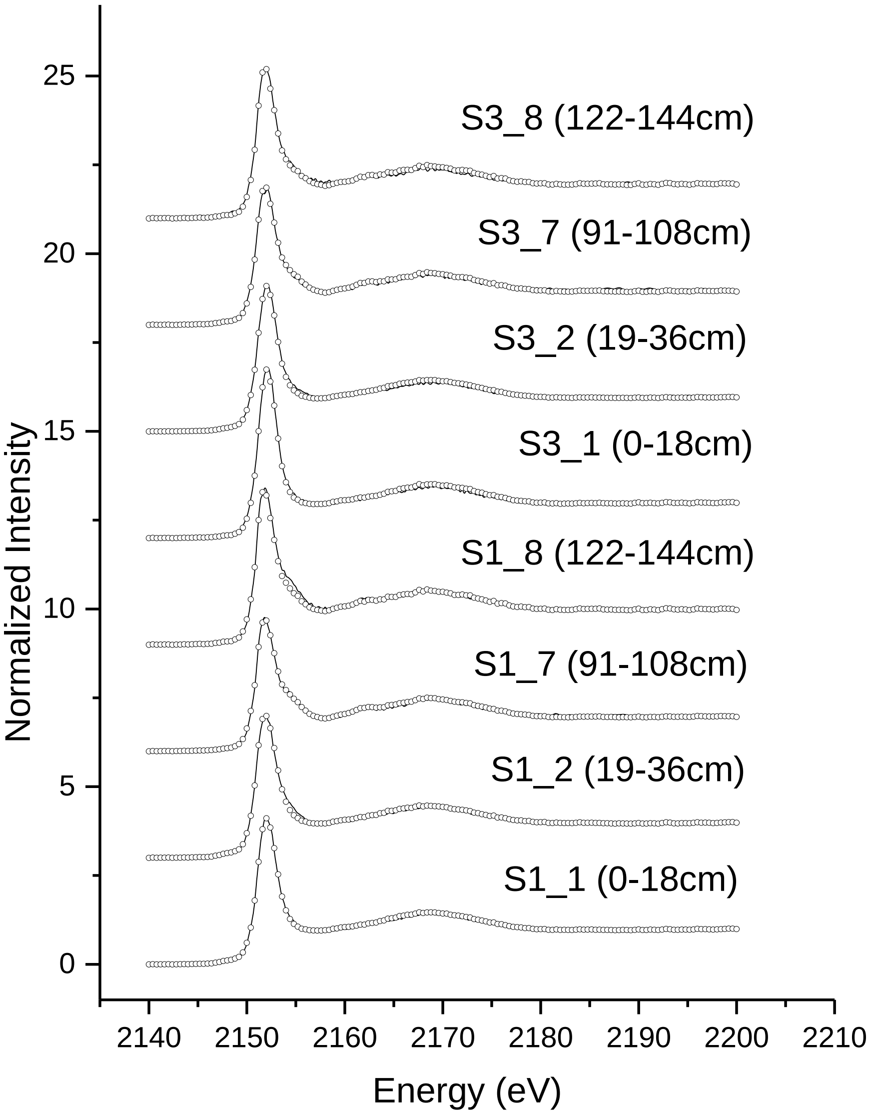

Fig. 16. Phosphorus K edge XANES analysis of selected depth of S1 and S3 samples. Solid lines and open circles represent normalized raw data and fit of the linear combination of reference compound fit analysis. The results are summarized in Table-2.

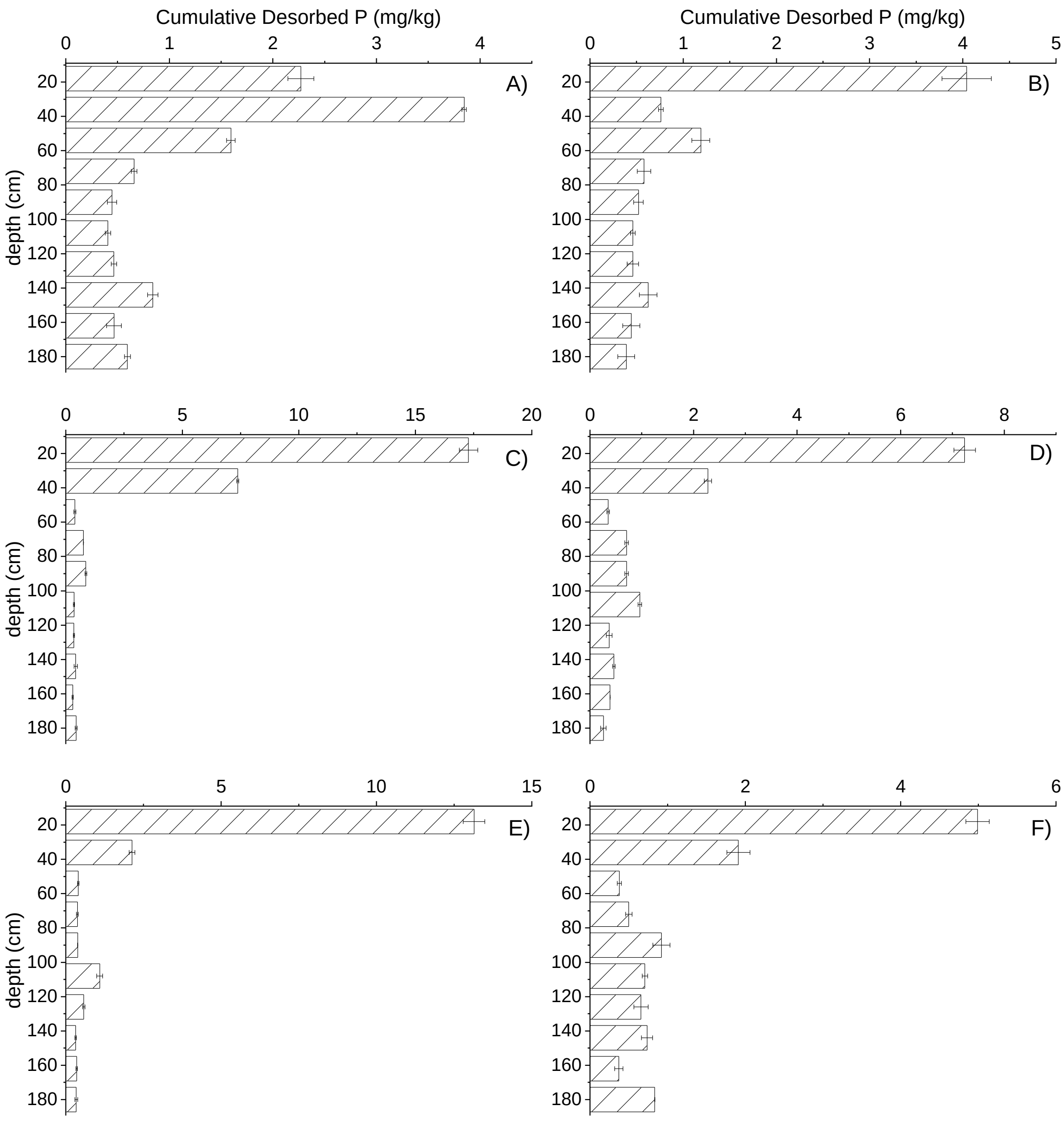

Fig. 17. Long-term (30-d) P desorption in the soil core samples (depth: 0-180 cm). A) soil core 1 (S1); B) soil core 2 (S2); C) soil core 3 (S3); D) soil core 4 (S4); E) soil core 5 (S5); F) soil core 6 (S6).

Table 2. Selected physicochemical properties and soil mineralogy of Douglas County soils. Surface soils represent soil depth 0-36 cm, and subsoils represent depth 36-180 cm.

Soil core	Soil layer	pH$_{water}$	CEC†	%base†	% IC‡	% OC‡	M3P§	Minerals¶
			cmol$_c$/kg	-------------%-------------			mg/kg	
S1	Surface	7.45 (±0.13)	25.27 (±2.94)	95.77 (±0.10)	0.12 (±0.02)	2.06 (±0.22)	11.00 (±4.08)	Q, M, V, I, K, Ch, Al, He
	Subsoil	8.01 (±0.22)	25.57 (±3.09)	96.23 (±0.23)	1.02 (±0.76)	0.68 (±0.29)	3.69 (±1.49)	Q, M, V, I, D, K, Ch, Ca, Al, He
S2	Surface	6.60 (±0.52)	30.51 (±3.20)	88.62 (±7.83)	0.19 (±0.12)	2.27 (±0.11)	14.00 (±6.93)	Q, M, V, K, Ch, Al
	Subsoil	8.04 (±0.26)	28.67 (±4.20)	96.15 (±0.83)	1.50 (±1.00)	0.78 (±0.39)	2.56 (±1.26)	Q, M, V, I, D, K, Ch, Ca, Al
S3	Surface	6.88 (±0.10)	25.24 (±2.73)	93.34 (±1.48)	0.46 (±0.20)	2.18 (±0.08)	40.57 (±7.27)	Q, M, V, K, Ch, Al
	Subsoil	7.81 (±0.50)	21.36 (±2.48)	95.58 (±1.42)	0.66 (±0.26)	0.88 (±0.20)	3.44 (±1.41)	Q, M, V, I, D, K, Ch, Al
S4	Surface	5.90 (±0.18)	30.23 (±2.19)	75.77 (±5.29)	0.08 (±0.04)	2.08 (±0.31)	26.50 (±11.12)	Q, M, V, I, Ch, Al
	Subsoil	7.61 (±0.46)	23.12 (±1.95)	95.30 (±1.51)	0.43 (±0.47)	0.75 (±0.26)	2.88 (±1.20)	Q, M, V, I, D, K, Ch, Al
S5	Surface	6.05 (±0.31)	31.86 (±1.38)	78.53 (±7.05)	0.40 (±0.11)	1.90 (±0.17)	41.50 (±26.64)	Q, M, V, I, D, K, Ch, Al
	Subsoil	7.69 (±0.48)	23.10 (±3.35)	95.61 (±1.15)	0.52 (±0.29)	0.73 (±0.23)	2.69 (±0.60)	Q, M, V, I, D, K, Ch, Al
S6	Surface	5.90 (±0.26)	31.72 (±2.20)	75.39 (±7.09)	0.48 (±0.07)	1.96 (±0.15)	23.50 (±8.74)	Q, M, V, I, K, Ch, Al
	Subsoil	7.78 (±0.60)	24.74 (±2.87)	95.40 (±2.11)	1.13 (±0.60)	0.77 (±0.29)	2.44 (±1.09)	Q, M, V, I, D, K, Ch, Ca, Al

† CEC = Cation exchange capacity; %base = percent base saturation.
‡ % OC = Organic carbon content; %IC = Inorganic carbon content.
§ M3P and M3Fe = Mehlich III extractable phosphorus and iron.

¶ Mineralogy determined by powder x-ray diffraction. Mineral abbreviation: Q – Quartz; M – Muscovite; V – Vermiculite; I – Illite; D – Dolomite; K – Kaolinite; Ch – Chlorite; Ca – Calcite; Al – Albite; He – Hematite; H –Hydroxyapatite.

Table-3: Results of Linear combination of reference compound fit of P K-edge XANES spectra (Fig. 4) of selected soil samples. Units are in %. Numbers in parenthesis

ID	P adsorbed calcite	P adsorbed gibbsite	Pyro-P	P adsorbed ferrihydrite	Phytic acid adsorbed ferrihydrite/gibbsite* /calcite#	Hydroxyl apatite	% Component sum (Reduced Ch^2)
S1_1	28.17(0.50)	23.81(0.54)	--------	--------	48.02(0.66)	--------	99.9 (0.0012)
S1_2	38.19(0.63)	--------	--------	--------	61.81(0.82)	--------	99.9 (0.0019)
S1_7	91.78(1.50)	--------	--------	8.22(1.18)	--------	--------	99.9 (0.0039)
S1_8	68.33(0.84)	1.49(0.76)	--------	--------	--------	30.18(0.62)	100 (0.0039)
S3_1	41.25(0.98)	33.28(1.12)	--------	--------	19.56(0.86), 5.76(1.12)*	--------	99.9 (0.0020)
S3_2	21.55(1.46)	32.99(1.44)	3.20(0.21)	8.50(1.44)	21.72(3.64), 21.02(3.42)#	--------	99.9 (0.0020)
S3_7	67.95(1.02)	--------	3.04(0.16)	6.17(1.91)	--------	18.61(1.79)	100 (0.0050)
S3_8	--------	--------	2.67(0.17)	9.85(0.74)	--------	37.19(0.761)	100 (0,.0011)

Highlights

- Depression depth is positively related to soil test P in the no-till system.
- There is a correlation between the tile DRP and the depression index if the structure of tile line covers the area correspond to depressions.
- Saturated hydraulic conductivity values were not positively correlated with soil test P values/depressions, but there is some evidence of preferential flow.
- P is accumulated in both surface and subsurface calcareous soils, and they are readily available in pore waters.
- Several organic P species (e.g., P-monoester) is abundant in surface and sub soils.
- Ca occluded inorganic P and Fe occluded inorganic P is abundant throughout the soil profile.

- Release of DRP and particulate P in soil profile is contributing to the seasonal P release in tile waters.

Current and future work in 2020

Objectives 1-3 are nearly completed. Manuscripts from Objectives 1 and 2 are currently in review, and the third manuscript from Objective 2 and 3 are currently in preparation. Two master students who are supported by this grant were graduating in 2019. To complete the project, a post doc is hired in 2020. In objective 3, we have characterized the physicochemical properties of soil core samples from Farm 6. We are also finding that the accumulation of P at the surface and subsurface, and the Ca/Fe occluded P is readily available. We are currently evaluating the data of physicochemical properties (e.g., depth sequence distribution of P) of subsurface soils in Farm 6. We continue to examine the processes responsible for seasonal DRP release to tile lines (Objective 3). In Farm 9, we observed that there was a large quantity of particulate P that was contributing to the season P release in tile waters. The preliminary assessment of particulate P suggests that PP is predominantly iron oxide associated P. Because of the presence of preferential flow, depth sequence distribution of labile P and PP become important. We are currently analyzing the quantity and speciation of water extractable DRP and PP as a function of depth. In upcoming months, we will be working on a final report at the conclusion of this project that will address each of the objectives stated above.

References cited:

Amundson, R., Guo, Y., & Gong, P. (2003). Soil diversity and land use in the United States. *Ecosystems*, *6*(5), 470–482. https://doi.org/10.1007/s10021-002-0160-2

Cade-Menun, B. J. (2015). Improved peak identification in 31P-NMR spectra of environmental samples with a standardized method and peak library. *Geoderma*, *257–258*, 102–114. https://doi.org/10.1016/j.geoderma.2014.12.016

Doolette, A. L., Smernik, R. J., & Dougherty, W. J. (2009). Spiking Improved Solution Phosphorus-31 Nuclear Magnetic Resonance Identification of Soil Phosphorus Compounds. *Soil Science Society of America Journal*, *73*(3), 919–927. https://doi.org/10.2136/sssaj2008.0192

Gentry, L.E., M.B. David, T.V. Royer, C.A. Mitchell, and K.M. Starks. 2007. Phosphorus transport pathways to streams in tile-drained agricultural watersheds. J. Environ. Qual. 36:408-415.

Guppy, C. N., Menzies, N. W., Moody, P. W., & Blamey, F. P. C. (2005). Competitive sorption reactions between phosphorus and organic matter in soil: A review. *Australian Journal of Soil Research*, *43*(2), 189–202. https://doi.org/10.1071/SR04049

Hao, X., Godlinski, F., & Chang, C. (2008). Distribution of Phosphorus Forms in Soil Following Long-term Continuous and Discontinuous Cattle Manure Applications. *Soil Science Society of America Journal*, *72*(1), 90–97. https://doi.org/10.2136/sssaj2006.0344

He, Z., Olk, D. C., & Cade-Menun, B. J. (2011). Forms and Lability of Phosphorus in Humic Acid Fractions of Hord Silt Loam Soil. *Soil Science Society of America Journal*, *75*(5), 1712–1722. https://doi.org/10.2136/sssaj2010.0355

Illinois Nutrient Loss Reduction Strategy. 2015. Illinois Environmental Protection Agency. http://www.epa.illinois.gov/topics/water-quality/watershed-management/excess-nutrients/index

King, K.W., M.R. Williams, M.L. Macrae, N.R. Fausey, J. Frankenberger, D.R. Smith, P.J.A. Kleinman, and L.C. Brown. 2015a. Phosphorus transport in agricultural subsurface drainage: a review. J. Environ. Qual. 44:467-485.

King, K.W., M.R. Williams, and N.R. Fausey. 2015b. Contributions of systematic tile drainage to watershed-scale phosphorus transport. J. Environ. Qual. 44:486-494.

MacCarthy, P., Malcolm, R. L., Clapp, C. E., & Bloom, P. R. (1990). An Introduction to Soil Humic Substances. In *Humic Substances in Soil and Crop Sciences: Selected Readings* (pp. 1–12). https://doi.org/10.2136/sssabookser7.c1

Martine, G.W. 1949. Soybeans. Edited by A. G. Norman. In Advances in Agronomy, Vol. 1. Academic press INC. New York.

Missong, A., Bol, R., Willbold, S., Siemens, J., & Klumpp, E. (2016). Phosphorus forms in forest soil colloids as revealed by liquid-state 31P-NMR. *Journal of Plant Nutrition and Soil Science*, *179*(2), 159–167. https://doi.org/10.1002/jpln.201500119

Rebsdorf, A., Thyssen, N., & Erlandsen, M. (1991). Regional and temporal variation in pH, alkalinity and carbon dioxide in Danish streams, related to soil type and land use. *Freshwater Biology*, *25*(3), 419–435. https://doi.org/10.1111/j.1365-2427.1991.tb01386.x

Reddy, K. R., Parupudi, U. S., Devulapalli, S. N., & Xu, C. Y. (1997). Effects of soil composition on the removal of chromium by electrokinetics. *Journal of Hazardous Materials*, *55*(1–3), 135–158. https://doi.org/10.1016/S0304-3894(97)00020-4

Rogovska, N. P., Blackmer, A. M., & Mallarino, A. P. (2007). Relationships between Soybean Yield, Soil pH, and Soil Carbonate Concentration. *Soil Science Society of America Journal*, *71*(4), 1251–1256. https://doi.org/10.2136/sssaj2006.0235

Rolfe, B. N., Miller, R. F. Mcqueen, I. S. 1960. Dispersion Characteristics of. Montmorillonite, Kaolinite, and Hike Clays in Waters of Varying Quality, and their Control with Phosphate. Dispersants. Shorter contributions to general geology. Geological survey professional paper 334-G.

Royer, T.V., M.B. David, and L.E. Gentry. 2006. Timing of riverine export of nitrate and phosphorus from agricultural watersheds in Illinois: implications for reducing nutrient loading to the Mississippi River. Environ. Sci. Technol. 40:4126-4131.

Schneider, K. D., Cade-Menun, B. J., Lynch, D. H., & Voroney, R. P. (2016). Soil Phosphorus

Forms from Organic and Conventional Forage Fields. *Soil Science Society of America Journal*, *80*(2), 328–340. https://doi.org/10.2136/sssaj2015.09.034

Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. J. Environ. Qual. 27:277–293.

Smith, D.D., 1947. The Effect of Crop Sequence on Erosion Under Individual Crops
Soil Science Society of America Journal. 11:532-538.

Turner, B. L., Mahieu, N., & Condron, L. M. (2003). Phosphorus-31 Nuclear Magnetic Resonance Spectral Assignments of Phosphorus. *Soil Sci. Soc. Am. J.*, *67*, 497–510.

USDA Soil Survey. (2006). Soil Survey of Douglas County, Illinois. In *Natural Accessibility Conservation Service*.

Xue, Y., M.B. David, L.E. Gentry, and D.A. Kovacic. 1998. Kinetics and modeling of dissolved phosphorus export from a tile-drained agricultural watershed. J. Environ. Qual. 27:917-922.