CEREAL RYE COVER CROPS MITIGATE SOIL PHOSPHORUS STRATIFICATION FROM LONG-TERM NO-TILLAGE

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ABSTRACT

Minimal or no-tillage is a widely adopted soil conservation practice and has been documented to reduce soil erosion, increase soil organic matter, and even reduce nutrient losses. Without tillage cultivation, however, phosphorus (P) can become stratified in surface soil layers and this may limit availability to crops or even increase bioavailable-P losses. Our primary objective was to measure the long-term (12-year) effects of long-term no-tillage (NT), cereal rye cover crops (CC), and their interaction on soil P stratification (SPS). We hypothesized: 1) NT would increase the stratification of bioavailable-P forms, and 2) CC would increase stratification compared to no cover crop under both conventional chisel plow tillage (CP) and NT via increased aboveground residue P inputs. There is not enough evidence in the literature to hypothesize about the NT × CC interaction. We sampled soils from a long-term, north central Iowa experiment with NT and cereal rye CC crossed factorially in place for 12 years resulting in the following treatments: 1) conventional CP tillage and no CC (CPWF), 2) NT also without CC (NTWF), 3) conventional CP tillage with a CC (CPCC), and 4) NT with the CC (NTCC). Soils were sampled to a depth of 10 in with increments at 0-1, 1-2, 2-4, 4-6, 6-8, and 8-10 in depths following both maize and soybean phases of the four treatments. These soils were analyzed for microbial biomass P (MB-P), anion exchange resin-P (AER-P), water extractable-P (WE-P), $NaHCO_3$ extractable-P ($NaHCO_3$-P), Mehlich 3 (M3-P), Olsen (Olsen-P), and Total-P. Soil P stratification varied across the soil P pools; but NT significantly stratified bioavailable-P pools such as WE-P, M3-P, and Olsen-P but not Total-P. Water extractable-P was most stratified with an average P stratification index (PSI) of 22.8. NTWF increased WE-P stratification by 584% compared to CPWF ($p < 0.001$). Although when NT was combined with CC (NTCC), it reduced this WE-P stratification by 88% ($p = 0.004$). Our findings confirm the plethora of previous work showing NT stratifies soil P, however, we show not equally for all forms of bioavailable-P and not for total-P. More importantly, we also show that cereal rye CCs can be a tool for ‘destratification’ of soil P, likely owing to cereal rye roots greater root uptake and re-distribution of surface P to lower depths during the shoulder seasons. This adds yet one more benefit of cereal cover crops, namely mitigating no-till SPS, when used in maize-soybean cropping systems in the Midwest US.

INTRODUCTION

Despite the many environmental and soil health benefits, no-tillage (NT) has some potential challenges, and one such challenge is that it redistributes or stratifies organic matter and non-mobile nutrients (Franzluebbers, 2002; Kay and VandenBygaart, 2002; Franzluebbers et al., 2007; Sá and Lal, 2009). One of the elements of most concern for stratification is the essential plant macronutrient phosphorus (P) – mostly because it is highly immobile and P fertilizer is applied as surface broadcast. In the long-term, annually deposited P —either from residues or fertilizers—tend to accumulate on the soil surface in conservation and reduced tillage systems as repeatedly observed in the literature (Zibilske et al., 2002; Bertol et al., 2007; Wright et al., 2007; Cade-Menun et al., 2015; Dang et al., 2015; Obour et al., 2017; Rahman et al., 2021). Two likely repercussions of soil P stratification (SPS) in soils are: 1) increased risk of higher runoff losses as dissolved reactive P and 2) crops may be P-limited if lateral roots cannot grow to access stratified bioavailable-P. In other studies, increased SPS was linked to increased bioactive-P losses in runoff (Smith et al., 2017; Daryanto et al., 2017a; Baker et al., 2017; Liu et al., 2019a). The majority of current SPS papers in the literature are related to the re-eutrophication of Lake Erie after a period of increased BMP implementation in the Lake Erie Basin.

MATERIALS AND METHODS

Site History and Treatments

In 2010 a long-term tillage and cover crop comparison experiment was established at the Agricultural Drainage Water Quality Research and Demonstration Site (ADWQDS) in Northwest Iowa by Gilmore City. The experiment has treatments represented in both maize (*Zea mays*) and soybean (*Glycine max L.*) phases of a maize-soybean rotation each year. The experiment uses a 2 × 2 factorial design with two factors – tillage and cover crops (CC). The factorial combination making four treatments: 1) conventional tillage with chisel plow and no cereal rye cover crop or winter fallow (CPWF), 2) no-tillage also without cover crop (NTWF), 3) conventional tillage with cereal rye (*Secale cereale.*) cover crop (CPCC), and 4) no-tillage with the cover crop (NTCC). The dominant soil types are Nicolet (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls), Webster (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls), and Canisteo (Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) clay loams.

Soil Sampling and Soil Physical Properties

Plots were sampled on April 21, 2022 when the average daily temperature was 50 °F and soils were thawing if not recently thawed. Soil sampling took place before any field activities that would have disturbed the soil. For each plot six soil core samples were taken in a zig-zagging diagonal pattern within the plant rows and interrows to avoid sampling over the buried subsurface drainage. The soil cores were transferred to plastic soil sampling sleeves 2.5 cm in diameter and 30 cm long to preserve the core’s shape and length. The soil tubes and soil were cut into six depth increments; 0-1, 1-2, 2-4, 4-6, 6-8, and 8-10 in, composited by depth, mixed, and passed through a 4 mm sieve field moist. Soil samples were then stored in a walk-in cooler (at ~ 39 °F) until extractions.

Soil Phosphorous Measurements and PSI

Microbial biomass phosphorous (MB-P) was determined using a chloroform fumigation method described in Jeannotte et al. (2004). The unfumigated portion used to determine MB-P were also analyzed ($NaHCO_3$-P). Plant available phosphates (AER-P) were determined using anion exchange membrane method described in Kovar et al. (2009) modified by measuring concentration using the malachite green method.

Deionized, water extractable-P (WE-P) was also performed to determine water-soluble orthophosphate, also described in Kovar et al. (2009), and modified to use the malachite green method. In addition, Mehlich-3-P (M3-P), Olsen-P, and total-P tests were performed by the Kansas State University Soil Testing Laboratory in Manhattan, KS.

Stratification indices were calculated for each plot to illustrate the severity of stratification for each phosphorous test. Phosphorous stratification indices (PSI) were calculated for each plot as

$$Phosphorus\ Stratification\ Index\ (PSI) = \frac{Concentration\ Average\ (0{-}5cm)}{Concentration\ Average\ (5{-}25cm)}.$$

RESULTS AND DISCUSSION

The crop phase had a significant effect on PSI, with soybean phase having 36% greater PSI on average compared to corn phase of the rotation. However, in partial support of our first hypothesis, 12 years of NT did increase SPS, measured as PSI, but only for some bioavailable-P pools and depended on if there was a CC or not. For example, NT only had a prominent effect on increasing the stratification of bioavailable-P (M3-P,Olsen-P, and WE-P) compared to chisel plow tillage (and in treatments without a CC – NTWF vs CPWF; Table 1). The NT soils had mean PSIs of 21.0 (range: 8.23 to 46.3) that were 28 to 584% greater than chisel plow across M3-P, Olsen-P, and WE-P tests and crop phases. This confirms previous literature showing NT and reduced tillage can more broadly stratify soil P.

Table 1. Average treatment PSIs with LSD values for significant results within each crop year.

Crop/Source	MB-P†	$NaHCO_3$-P	AER-P†	WE-P†	M3-P†	Olsen-P	Total-P
Soybean Year							
CPWF	1.78	18.02	1.44	7.80c	6.45c	5.88b	1.51
CPCC	3.27	14.92	2.92	28.95b	8.80a	9.03ab	1.63
NTWF	4.70	21.54	3.35	66.12a	9.25a	9.69a	1.61
NTCC	4.26	11.48	2.94	18.53b	7.75b	7.23ab	1.61
Maize Year							
CPWF	2.22	5.91	1.90	5.73d	6.91	6.94	1.40
CPCC	3.15	16.15	2.08	20.97b	7.57	7.72	1.52
NTWF	2.98	9.35	2.53	26.41a	7.94	6.79	1.53
NTCC	2.68	8.02	2.54	7.73c	5.39	5.23	1.47

†:MB-P = Microbial Biomass-P, $NaHCO_3$-P = sodium bicarbonate extractable P, AER-P = Anion Exchange Resin-P, WE-P = Water Extractable-P, M3-P = Mehlich-3 P.

In support of our second hypothesis, CCs had some minor effects on SPS. Although significant effects were infrequent, across crop phases and P tests, PSIs were 67% greater in chisel-plow soils with a CC than without (CPCC vs CPWF) (Table 1. and Figure 1.). In addition, WE-P, M3-P, and Olsen-P, CPCC was either significantly or marginally greater (only WE-P in maize) than conventional tillage without a CC by 107% on average (Table 1.). This is likely due to freeze-thaw processes acting upon the living biomass, leaching inorganic and organic bioactive-P into the soil. It could also be due to the annual deposition of P from terminated aboveground biomass. This aligns with

Bechmann et al. (2005) that found cereal rye CC increased bioavailable-P on the soil surface compared to bare and manured soils. Increased leaching of bioactive-P released from CC in temperate regions has been observed in other studies as well (Miller et al., 1994; Cober et al., 2018; Liu et al., 2019b; Sun et al., 2019). Assuming leached P is not mobile and accumulates in surface soils, then surface CC residues in CP may increase PSIs.

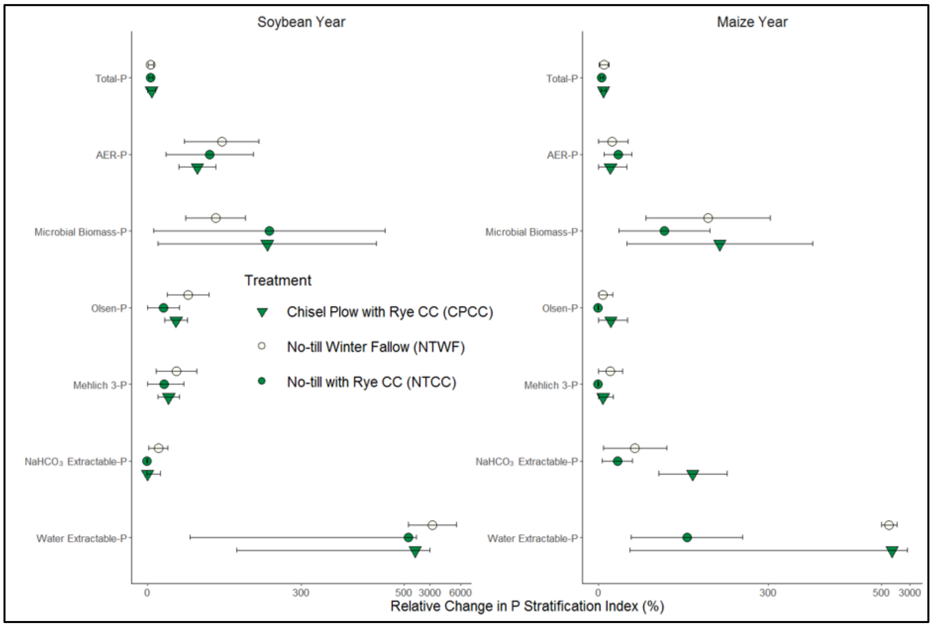

Figure 1. Relative change in soil phosphorus stratification index (PSI) in both soybean (left panel) and maize (right panel) phases of the rotation. Relative change was calculated as PSI of three treatments relative to the ‘business-as-usual’ treatment or Chisel Plow Winter Fallow (CPWF). AER-P = Anion exchange resin P.

Adding cereal rye CC to NT did decrease PSI for select soil P pools (Table 1.). For example, adding cereal rye CC to NT (NTCC) decreased PSIs for WE-P and M3-P by 72 and 24% respectively compared to NT without a CC (NTWF). This reduction in SPS was likely due to uptake and redistribution into the CC and microbial biomass (Rahman et al., 2021). Living roots in alkaline soils (which these are, mean pH = 7.5) could also modify pH of the rhizosphere and exude H^+, acidifying this surrounding soil and releasing Ca-bound phosphate (Gahoonia et al., 1992). This would mobilize and increase the amount of bioactive-P in the rhizosphere, perhaps redistributing it with depth as CC roots grew deeper into the soil.

Based on our findings, conservation practices of both NT and CC alone can stratify bioavailable-P but not total P. Moreover, and what is even more interesting is that when NT and CC are combined in an interaction, there is a negative effect on bioavailable-P stratification for some P pools (Table 1). In other words, by combining the two conservation practices you can alleviate P stratification issues. Further work is needed to link stratification of bioavailable-P to water quality issues and plant P uptake in order to further fine-tune conservation management and P use efficiency.

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