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Soil and crop response to phosphorus and potassium management under conservation tillage

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Abstract

In conservation tillage systems, proper fertilizer phosphorus (P) and potassium (K) management is critical to optimize yield and minimize negative environmental impacts. The objective of this study was to assess the responses of crop yield, nutrient use efficiencies, root growth, and soil test P and K levels to tillage, fertilizer placement, and fertilizer rates in a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation. Experiments were conducted for 8 yr in Illinois with tillage/fertilizer placement as the main plot (no-till/broadcast [NTBC], strip-till/broadcast [STBC], and strip-till/deep band [STDB]) and PK fertilizer rates as the subplot. The NTBC treatment consistently reduced yields in corn by 6.2 and 4.5% and in soybean by 3.1 and 6.1% relative to STBC and STDB, respectively. Also, NTBC had greater root length density at in-row and between-row positions relative to STBC and STDB. Nutrient use efficiency indices (partial nutrient balance, agronomic efficiency, and partial factor productivity) declined with increasing P and K rates but were not affected by tillage/fertilizer placement treatments. Deep banding significantly reduced soil P and K concentrations in surface layers while increasing them at the depth of application. These results underscore the reported potential for deep banding combined with strip-till to improve conditions for nutrient uptake while reducing the risk for nutrient losses to the environment. Critical soil test P and K levels (21 mg P kg^{-1} and 217 mg K kg^{-1}) were similar for P and greater for K than the current university recommendations, which highlights the need for continuous refinement of soil fertility recommendations to keep pace with changes in production technologies and yield levels.

1 | INTRODUCTION

Effective management of phosphorus (P) and potassium (K) fertilizer is essential to balance high-yielding crop production, profitability, and environmental tradeoffs (Khan et al., 2018). Previous research has shown that in-field management strategies related to tillage and fertilizer placement/rate have the potential to reduce P losses in major crop production regions of the world such as the U.S. Midwest, where conservation tillage and subsurface fertilizer P placement are

Abbreviations: AE, agronomic efficiency; BR, between row; EXP, exponential; IR, in row; KUE, potassium use efficiency; LP, linear plateau; MRD, mean root diameter; NTBC, no-till/broadcast; PFP, partial factor productivity; PNB, partial nutrient balance; PUE, phosphorus use efficiency; QP, quadratic plateau; RLD, root length density; RSD, root surface density; STBC, strip-till/broadcast; STDB, strip-till/deep-band; STK, soil test potassium; STP, soil test phosphorus; TP, tillage/fertilizer placement.

emphasized for state-level nutrient loss reduction strategies. However, these strategies are largely focused on water quality outcomes, and important questions remain about managing P placement in conservation tillage systems to effectively balance agronomic and environmental goals. In particular, fertilizer P and K management can be challenging due to limited soil disturbance and the stratification of nutrients over time (Díaz-Zorita & Grove, 2002; Li et al., 2017). Hence, an integrated understanding of soil nutrient dynamics, crop productivity, root distribution in the soil profile, and partial nutrient balances is required to guide crop management decisions and to improve P and K use efficiency.

Core Ideas

- No-till reduced yield relative to strip-till.
- Deep banding P and K with strip-till resulted in no yield advantage over broadcast applications.
- Although there is no agronomic advantage, deep banding effectively reduced soil P and K levels in soil surface layers.
- Critical soil test K levels were greater than current recommendations.

Conservation tillage practices like no-till and strip till have been adopted by many producers to save operational costs, reduce soil erosion, and conserve soil water (Fernández, Sorensen, & Villamil, 2015; Morrison, 2002). The adoption of deep banding of P and K fertilizers for conservation tillage systems has been hypothesized to increase nutrient availability and thus to enhance crop productivity and fertilizer use efficiency (Mallarino & Murrell, 1998; Yin & Vyn, 2002). From an environmental perspective, deep banding is considered to be ideal in terms of eliminating nutrient stratification and reducing the potential for surface runoff of fertilizer P (Kimmell, Pierzynski, Janssen, & Barnes, 2001; Randall & Vetsch, 2008; Yuan, Fernández, Pittelkow, Greer, & Schaefer, 2018). However, because many studies on fertilizer placement have reported conflicting results regarding crop performance in comparison to broadcast fertilizer, requirements for effective fertilizer placement remain unclear. Several studies have reported increased grain yield and nutrient accumulation with deep banding of fertilizers relative to broadcast (Farmaha, Fernández, & Nafziger, 2012a; Hansel, Diaz, Amado, & Rosso, 2017; Kang, Yue, & Shi-qing, 2014; Nkebiwe, Weinmann, Bar-Tal, & Muller, 2016), whereas others found no differences or inconsistent results (Bordoli & Mallarino, 1998; Randall & Vetsch, 2008; Yin & Vyn, 2002). As summarized by several reviews (Ma, Rengel, & Rose, 2009; Nkebiwe et al., 2016; Randall & Hoeft, 1988), the effectiveness of deep placement of fertilizers may be determined by factors including climatic condition, soil texture, tillage, fertilizing history, nutrient mobility, and crop species. These variable findings suggest that further work is essential to understand the effects of deep banding in relation to edaphic and climatic conditions, soil management, and plant–soil interactions to maximize yield benefits and, in the case of soil P concentrations, to minimize environmental risk.

One limitation of previous research is the relatively short duration of field experiments. Although placement of low-mobile nutrients like P and K largely influences their distribution within the soil, changes in soil P and K levels are also influenced by the cumulative effects of soil–root interactions, crop nutrient accumulation, and grain nutrient removal over many years (Messiga et al., 2012). Previous studies have shown large variability in long-term changes in soil P and K concentrations in different regions under various fertilization management practices (Dodd & Mallarino, 2005; Khan et al., 2018; Messiga et al., 2012; Randall, Iragavarapu, & Evans, 1997). However, the effect of deep banding of P and K fertilizer has received little attention in strip-till systems (i.e., comparing strip-till/broadcast [STBC] with strip-till/deep-band [STDB]). The performance of deep banding and broadcast P and K fertilizer application in a no-till system (no-till/broadcast [NTBC] and no-till/deep band), as well as deep banding with strip-till (STDB) in a corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation in Illinois, has been evaluated in 3- to 4-yr studies (Farmaha, Fernández, & Nafziger, 2011, 2012a, 2012b; Fernández & White, 2012). In general, no yield benefit with deep banding relative to broadcast in no-till was found, whereas strip-till provided an advantage for yield in both corn and soybean due to improved rooting conditions for nutrient and water uptake relative to no-till treatments when fertilizer was broadcast. Investigation of the effect of deep banding of P and K fertilizer is timely given continuous yield increases in recent decades combined with the introduction of new plant genetics and crop management technologies, raising the question of whether historical guidelines for maintaining soil P and K levels remain accurate. On-farm experiments that are representative of commercial production are necessary to assess changes in crop nutrient uptake and removal in relation to changes in soil P and K levels across a gradient of P and K fertilizer inputs.

Considering the nonrenewable nature of P and K reserves coupled with growing P and K deficiencies worldwide due to low soil availability and increased farmland (Batjes, 1997; Naseem, Baber, Ahmed, Akram, & Tareen, 2014; Randall et al., 1997a), there is a clear need to increase P use efficiency (PUE) and K use efficiency (KUE). Dhillon, Torres, Driver, Figueiredo, and Raun (2017) reported PUE using balance and difference methods in cereal crops to estimate a benchmark at a global scale and highlighted improved management strategies, including banding P fertilizer with the seed and foliar P application, to increase PUE and mitigate environmental problems associated with excess P inputs. Other studies have assessed the effects of K fertilizer rates on KUE at field or regional scales (Ahmad, Ahmad, Ali, Ishaque, & Rehman, 2012; Naseem et al., 2014). Peterson, Sander, Grabouski, and Hooker (1981) compared broadcast and banded P fertilization in winter wheat in P-deficient soils and reported higher efficiency for banded applications. However, to our knowledge information is lacking regarding benchmark PUE and KUE parameters for different tillage and fertilizer placement practices for corn and soybean production in the U.S. Midwest.

Understanding long-term soil P and K dynamics under various management systems is critical to manage nutrients more efficiently. Abundant studies have focused on evaluating changes on soil P and K levels over time with different fertilization rates (Anthony, Malzer, Zhang, & Sparrow, 2012; Dodd & Mallarino, 2005; Gallet, Flisch, Ryser, Frossard, & Sinaj, 2003; Jouany, Colomb, & Bose, 1996; Webb, Mallarino, & Blackmer, 1992). These studies showed large variability in the incline/decrease dynamics of soil P and K over time, highly dependent on the PK fertilization rate, climatic conditions, soil properties, soil test method, evaluation time, and crop removal rate (Ciampitti & García, 2011). However, comparatively fewer studies have been conducted to assess the long-term soil P and K dynamics with various fertilizer placement methods combined with conservation tillage. Even less is known about the impact of tillage and P and K placement on root development and nutrient acquisition (Farmaha et al., 2012a; Fernandez & White, 2012). Some studies focused on relating the yield responses to fertilizer placement with initial soil P and K levels in long-term no-till and found that P increased yields only in low initial soil test P levels with no response to P placement (Bordoli & Mallarino, 1998), whereas K increased yields in soils that tested optimum or higher in soil test K levels, and yields were higher when K was deep or shallow banded (Bordoli & Mallarino, 1998; Vyn & Janovicek, 2001). Messiga et al. (2012) found that no-till maintained higher soil test P levels on the top 0- to 10-cm layers compared with conventional tillage in 11 yr in Canada. Hansel et al. (2017) found that STDB increased soil test P levels by 11–19% at the 15- to 25-cm layer, whereas NTBC increased soil test P by 36–43 and 36% at the 0- to 5-cm layer in Brazil in 2014 to 2015. Long-term studies are lacking to evaluate the soil test P (STP) and soil test K (STK) levels over time at different depths and row positions under various P and K management strategies in conservation tillage. Moreover, in light of greater yields and changes in technology, our current knowledge is limited regarding the maintenance rate and critical concentrations of STP and STK needed for these new conditions.

Despite the potential for conservation tillage and subsurface P placement to improve water quality, the long-term effects of different tillage/fertilizer placement combinations on crop performance and changes in soil P and K levels remain uncertain. The objectives of this study were to systematically determine the responses of grain yield, root growth, P and K nutrient accumulation and nutrient use efficiencies, and STP and STK levels to tillage, P and K rates, and fertilizer placement in commercial corn–soybean rotations in Illinois. Given recent changes in production levels in this region, an additional objective was to determine the critical concentrations of STP and STK for maintaining corn and soybean yields as compared to currently recommended values.

2 | MATERIALS AND METHODS

2.1 | Field experiment design

The study was conducted between fall 2007 and fall 2015 in three commercial fields near the village of Pesotum in east-central Illinois. The three locations had similar soils and were within a 2-km radius of each other, with each site having a combination of Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll) and Flanagan silt loam (fine, smectitic, mesic Aquic Argiudolls) soils. Each field was managed in a corn–soybean rotation with 76-cm row spacing for both crops. Each site had soybeans during the 2007 growing season before the start of the 8-yr study; thus, corn was the first crop planted after treatment establishment.

The study was set up as a split-plot arrangement in a randomized complete-block design with two replications at each site. Plot size was 6 × 150 m, and treatments remained in the same plot for the duration of the study. The main (whole) plot included three tillage/fertilizer placement treatments: NTBC, strip-till/broadcast (STBC), and strip-till/deep-band (STDB). Strip-till operations were performed in the fall, and the crop was planted on the location of the strips the following spring. Strip-till was performed on 76-cm row spacing using a strip-till toolbar (DMI, Model 4300) and form a residue-free berm approximately 5–8 cm tall and 25 cm wide. The location of crop rows was maintained every year. Broadcast applications were done with a drop spreader (10T Series, Gandy). For the STBC treatment, broadcast applications were performed after the strip-till operation. For the STDB treatment, the fertilizer was banded 15 cm below the soil surface during the tillage operation using a Gandy Orbit Air applicator (Model 6212C). The split-plot treatments were blends of triple superphosphate (0-45-0; N–P_2O_5–K_2O) as the P source and KCl (0-0-60; N–P_2O_5–K_2O) as the K source made to create the following P–K fertilizer treatments: a control receiving no P or K (0-0 or check) and six additional rates ranging from 50 to 175 kg P_2O_5 ha^{-1} and K_2O ha^{-1}, established in 25 kg P_2O_5 and K_2O ha^{-1} increments. These rates were applied every other year after soybean harvest except in 2013 and 2014, when P and K were applied each fall at half the rate. The corn crop also received a uniform application of 200 kg N ha^{-1} following current guidelines (Fernández, Brouder, Volenec, Beyrouty, & Hoyum, 2009).

2.2 | Measurements

Soil samples for P and K analysis were collected from 2007 to 2015 from all treatments at each site every fall after harvest, except in 2009 when soil samples were collected in the spring because wet soil conditions in the fall prevented access to the field before the soils froze. To account for spatial differences in soil test levels due to tillage and fertilizer placement treatments, a composite of 12 soil cores (2 cm diam. each) was made in row (IR) and at each of three positions moving away from the crop row in 19-cm increments (19, 38, and 57 cm from the IR). Hereafter, these between-row (BR) positions are referred to as BR-19, BR-38, and BR-57. For each sampling event, cores were divided into depth increments of 0–10, 10–20, and 20–30 cm. Soil samples were collected from a 3 × 3 m area within each plot, and the same area was used across the 8-yr study. Soil samples were air dried, ground to pass through a 2-mm sieve, and analyzed for P with Mehlich-III extraction and spectrophotometer analysis following the NCERA-13 method (Frank, Beegle, & Denning, 1998) and analyzed for K with 1 M NH_4OAc extraction (Warncke & Brown, 1998) and analyzed by atomic absorption spectrometer.

To evaluate root growth, root samples were collected from 2008 to 2010 in two treatments (the 0-0 and 125-125 kg P_2O_5–K_2O ha^{-1} rate). Root samples were collected by extracting three-core (2.5 cm diam.) composite samples from the 0- to 5-, 5- to 10-, and 10- to 30-cm soil depth increments at IR and BR-38 positions at the VT development stage for corn and at R1 for soybean. Roots were separated from the soil with a semiautomatic hydropneumatic elutriation system (Gillison's Variety Fabrication, Inc.), and roots were collected in 410-µm sieves (Smucker, McBurney, & Srivastava, 1982). The content of the sieve was transferred to a shallow tray where organic debris was manually removed. Root samples were stored in 25% (v/v) ethanol at 5°C. Root length, root surface area, and mean root diameter (MRD) were measured, and root length density (RLD) and root surface area density (RSD) were calculated with an Epson Expression 10000XL scanner (Model EU-88) and Win-RHIZO software (Regent Instruments Inc.).

Machine harvest was performed on the four center rows of each plot. Corn grain yields were adjusted to 155 g kg^{-1} moisture and soybean yields were adjusted to 130 g kg^{-1} moisture. Grain samples were oven dried (60°C until constant weight), ground to pass a 1-mm mesh screen with a Wiley mill (Standard Model 3, Arthur H. Thomas Co.), and chemically analyzed for P and K content by nitric acid–perchloric acid mixture (HNO_3–$HClO_4$) digestion followed by inductively coupled plasma spectrometry following the official methods of analysis of AOAC International (Horwitz, 2000).

2.3 | Data analysis

Calculations of nutrient use efficiency followed the methods described in Fixen et al. (2014). Partial nutrient balance (PNB) was expressed as nutrient output per unit of nutrient input (a ratio of "removal to use") (Equation 1). Agronomic efficiency (AE) is calculated in units of yield increase per unit of nutrient applied (Equation 2). Partial factor productivity (PFP) is a production efficiency expression calculated in units of crop yield per unit of nutrient applied (Equation 3). Partial nutrient balance measures nutrient removal to nutrient use, and AE and PFP consider crop response to a nutrient addition (Fixen et al., 2014).

$$\text{PNB} = U_\text{H}/\text{F} \tag{1}$$

$$\text{AE} = \left(Y - Y_0\right)/F \tag{2}$$

$$\text{PFP} = Y/F \tag{3}$$

where U_H indicates the quantity of nutrient removed (P or K) in the harvested portion of the crop, F indicates the amount of nutrient applied (elemental P and K), Y indicates yield of harvested portion of crop with nutrient applied, and Y_0 indicates yield with not nutrient applied.

Treatment effects on crop yield, grain P and K concentration and accumulation, and nutrient use efficiencies were assessed by ANOVA using R software version 3.2.1 (R Core Team, 2015). The main effects include tillage/fertilizer placement treatments (TP) and PK rates (PK) and their interaction (TP × PK). Blocks were nested within years, and because initial data analysis suggested that treatment responses were similar across each year, model terms for year, site, block, and their interactions with main effects were considered random. Means comparison tests were done following the Tukey's Studentized range honestly significant difference test using the agricolae package (Mendiburu, 2015). Treatment effects were declared significant at $\alpha = .1$.

Determination of critical STP and STK concentrations followed the method in Dodd and Mallarino (2005), with linear plateau (LP), quadratic plateau (QP), and Mitscherlinch exponential (EXP) models fit to relationships between STP/STK and relative yield using the "easynls" package in R (R Core Team, 2012). Relative yield was defined as the mean yield of plots receiving 0 PK expressed as a percentage of the mean yield of plots that received the highest annual P and K rate. For critical STP and STK in each crop, two datasets were used to develop the quadratic-plateau models: the 0-0 PK dataset only included yield, and soil data from the treatments received no P and K fertilizer.

The 8-yr STP and STK means on the 0- to 20-cm layers averaged across crop-row positions and tillage/fertilizer placement treatments for seven P and K rates were fitted against time using linear models in R (R Core Team, 2012). Because no annual P and K rate maintained STP and STK, the gross maintenance P and K rate from this study was calculated by interpolating from linear coefficients of equations fit to relationships between STP/STK and time for the two annual P rates that encompassed the unknown maintenance rate (with STP/STK increasing in one equation and decreasing in the other). The calculation is shown in Equation 4:

$$\text{Maintenance rate (kg P/K ha}^{-1}\text{yr}^{-1}) = P_{\text{dec}} + \left\{-b_{\text{dec}}/\left[\left(b_{\text{inc}} - b_{\text{dec}}\right)/\left(P_{\text{inc}} - P_{\text{dec}}\right)\right]\right\} \quad (4)$$

where P_{dec} is the P/K rate (kg P/K ha^{-1} yr^{-1}) resulting in decreasing STP/STK, P_{inc} is the P/K rate resulting in increasing STP/STK, b_{dec} is the linear coefficient of the equation for decreasing STP/STK, and b_{inc} is the linear coefficient of the equation for increasing STP/STK (Dodd & Mallarino, 2005).

3 | RESULTS AND DISCUSSION

3.1 | Crop yield, nutrient accumulation, and nutrient use efficiency

Crop yield was significantly affected by TP and P and K rate (PK) in both corn and soybean, but no TP × PK interaction was detected (Table 1). Overall, for corn, STBC produced 6.6% and STDB 4.7% greater grain yield than NTBC; for soybean, STBC produced 3.2% and STDB 6.5% greater yield than NTBC (Table 1). The lowest yield with no-till relative to other treatments was consistent across 8 yr in both crops (data not shown). The yield variability across sites was small, with the SD between sites within each year ranging from 0.92 to 1.13 Mg ha^{-1} for corn and from 0.36 to 0.69 Mg ha^{-1} for soybean. The advantage for corn and soybean production with strip-till relative to no-till is consistent with other studies (Farmaha et al., 2011; Fernández & White, 2012), whereas others found no yield differences among strip-till and no-till (Hoeft et al., 2000; Vetsch & Randall, 2002). The yield reduction in no-till relative to strip-till in our study is possibly due to the cooler and wetter soil conditions from no-till in early spring, which may contribute to delayed emergence and yield reduction (Buman, Alesii, Hatfield, & Karlen, 2004). Another possible explanation may be attributed to enhanced nutrient uptake, soil organic matter, water use efficiency, water filtration, and water storage capacity with strip-till relative to no-till (Fernández & White, 2012; Fernández et al., 2015; Lipiec, Kuś, Słowińska-Jurkiewicz, & Nosalewicz, 2006; Liu, Zhang, Yang, & Drury, 2013; Messiga et al., 2012; Ziadi et al., 2014).

There was no evidence that nutrient placement had an effect on corn or soybean yield for strip-till (Table 1), which is in agreement with previous reports in corn (Fernández & White, 2012; Rehm & Lamb, 2004) and soybean (Farmaha et al., 2011; Hansel et al., 2017; Yin & Vyn, 2002). However, these results are in contrast with some studies that have reported a yield advantage with deep banding (Farmaha, Fernández, & Nafziger, 2012b; Kang et al., 2014). Earlier reviews concluded that deep banding of fertilizers typically outperformed broadcast applications in fields with low fertility or insufficient rainfall but that the benefit was small or nonexistent on soils with optimum or high fertility (Ma et al., 2009; Randall & Hoeft, 1988). Starting soil P and K levels (STP and STK) in the top 20 cm were 21 and 151 mg kg^{-1}, respectively, both being near the recommend critical P value of 20 mg kg^{-1} and the K value of 150 mg kg^{-1} to maximize yield (Fernández & Hoeft, 2009). Thus, adequate starting P and K soil test values may be responsible for the lack of response to P and K fertilizer placement method observed here.

Increasing P and K rate did not significantly affect corn and soybean yields beyond the unfertilized treatment (Table 1). Moreover, our results demonstrate how soil P and K levels can decline without adequate P and K inputs within an 8-yr time frame, negatively affecting yields. Toward the end of the study, all of the fertilized treatments maintained soil P and K levels above the critical values, yet soil P and K levels had dropped to suboptimal (9.7 mg P kg^{-1} and 131.5 mg K kg^{-1}) for the unfertilized check by 2015 (Figure 1). This change in values likely explained the significantly lower yield in the check for both corn and soybean (Table 1).

In this study, grain P and K concentrations for corn and soybean were not affected by tillage/fertilizer placement (data not shown); nor was the accumulation for soybean (Table 1). However, in corn, P accumulation in STBC was ∼4% greater than NTBC and 2% greater than STDB, and K accumulation in STBC was 5% greater than NTBC.

In this study, grain P and K accumulation for corn and soybean (Table 1) were not affected by tillage or fertilizer placement, although corn P accumulation in STBC was ∼4% greater than NTBC and 2% greater than STDB and K accumulation in STBC was 5% greater than NTBC numerically (Table 1). Grain P and K concentrations showed a similar pattern to accumulation; thus, only the accumulation data are presented. The mean P and K concentrations for corn were 0.23 mg P kg^{-1} and 0.36 mg K kg^{-1}, and mean P and K concentrations for soybean were 0.55 mg P kg^{-1} and 1.95 mg K kg^{-1}. Increasing fertilizer P and K rate significantly increased grain P accumulation in both crops, with the most noticeable increase typically occurring between the check and the first rate of PK fertilizer (Table 1). Nutrient accumulation is an important parameter to determine nutrient removal and the need to replenish soil fertility, particularly in high-yielding cropping systems. Grain P and K accumulation increased linearly with P and K rates in both crops (Table 1) and is consistent with what is expected for the relationship that exists

TABLE 1 Treatment means and analysis of variance results for grain yield and grain P and K accumulation in corn and soybean as affected by tillage/fertilizer placement or P and K fertilizer rate

	Corn			Soybean		
	Yield	Grain P accumulation	Grain K accumulation	Yield	Grain P accumulation	Grain K accumulation
Tillage placement (TP)[a]	Mg ha^{-1}	kg ha^{-1}		Mg ha^{-1}	kg ha^{-1}	
NTBC	10.6b[b]	24.4b	39.4b	3.1b	17.2a	61.6a
STBC	11.3a	25.4a	41.3a	3.2a	17.9a	64.3a
STDB	11.1a	24.8b	40.7ab	3.3a	17.7a	64.3a
PK rate (PK)						
0	10.3b	20.7b	35.7b	3.1b	15.5b	58.6b
50	10.9a	24.7a	40.5ab	3.3a	17.1ab	62.4ab
75	11.3a	24.8a	40.7ab	3.3a	17.9a	64.6a
100	11.1a	25.3a	41.1ab	3.3a	17.7ab	63.8a
125	11.1a	25.1a	40.9ab	3.3a	18.0a	64.4a
150	11.1a	26.5a	42.3a	3.3a	18.2a	64.6a
175	11.2a	26.8a	42.4a	3.3a	18.5a	65.4a
	ANOVA (P > F)					
Source of variation						
TP	.038	.011	.039	.034	.357	.381
PK	.049	<.001	.048	.041	<.001	.012
TP × PK	1.000	.999	1.000	1.000	.830	.973

Note. Data are averaged over three sites and 8 yr (2007–2015).
[a]NTBC, no-till/broadcast; STBC, strip-till/broadcast; STDB strip-till/deep band.
[b]Same letters within a column and treatment parameter indicate no significant difference.

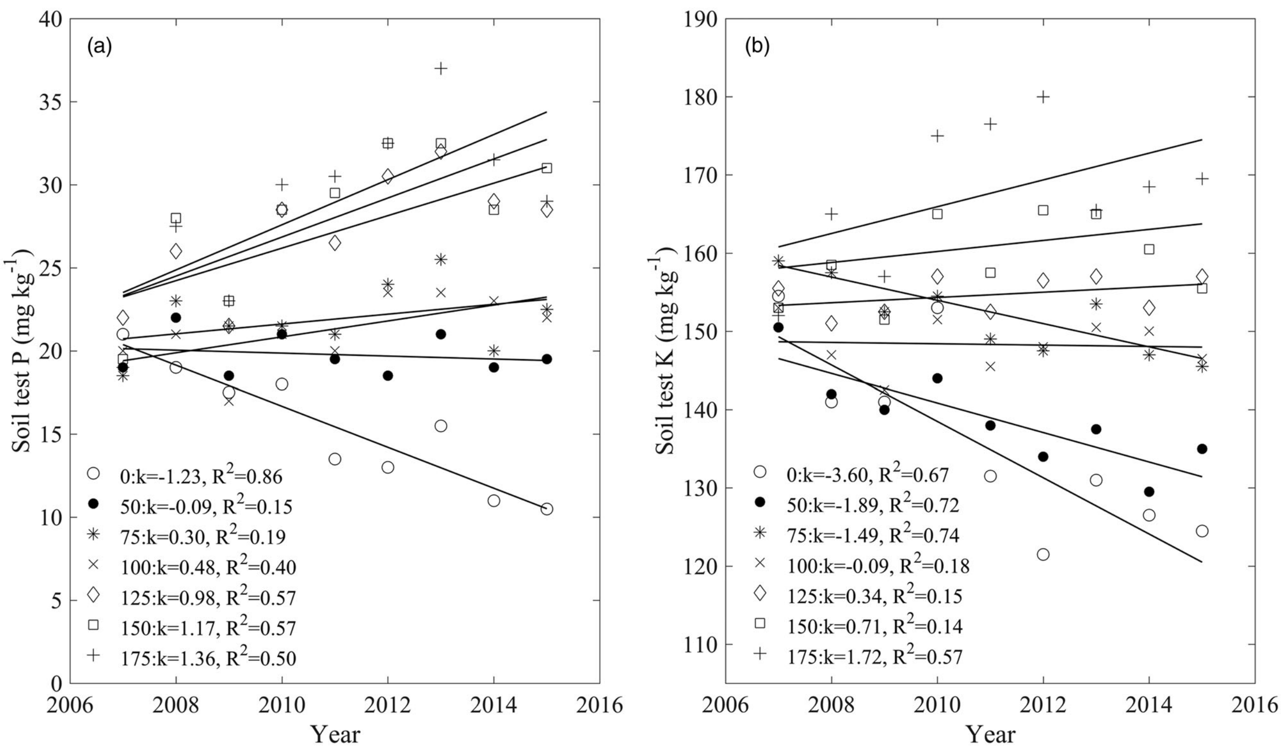

FIGURE 1 Soil-test P (a) and K (b) changes over time in the top 0- to 20-cm layer averaged across different tillage/fertilizer placement treatments and positions with respect to the row for seven P and K fertilizer rates. The letter "k" indicates the slope of the linear regression. Data are averaged over three sites and 8 yr (2007–2015)

between soil supply and crop nutrient uptake. Of interest is that, except for the low P and K rate treatments, soil test values did not drop below critical values, yet crop nutrient uptake continued to respond positively to increasing nutrient inputs. However, this did not translate to yield benefits. Fernández and White (2012) found that STDB effectively improved conditions for crop P and K accumulation relative to the no-till treatments in corn, which agrees with the result in this study.

Tillage and fertilizer placement and P and K rates significantly affected P and K use efficiencies (Table 2). All three efficiency parameters showed an exponential decrease in response to increasing P and K rates (data not shown). The STBC treatments had significantly higher values for PNB of K and PFP in corn and PFP in soybean, ranging from 1.5 to 33.7% higher than those in the other two practices. This difference was a direct result of the observed yield increases for these tillage/fertilizer placement treatments in each crop. However, in contrast to prior studies that found significantly greater PNB with banded P fertilization (Dhillon et al., 2017; Hansel et al., 2017; Peterson et al., 1981; Sander, Penas, & Eghball, 1990), we did not find an advantage of deep banding for PNB or AE compared with broadcast applications (STBC and STDB in Table 2), indicating a similar ability of nutrient removal and yield increase per unit of nutrient applied between the two fertilizer placement methods. This might be due to the optimal soil fertility starting conditions. Furthermore, the fact that most of the nutrient uptake occurs in the soil surface regardless of placement highlights the reason why there was no effect of placement. It is important to point out that even when fertilizer is subsurface banded, a large amount of nutrients are cycled back to the soil surface in the form of crop residue, so the surface layer tends to have higher P and K levels than the subsurface even when banding. Because deep banding of P does not reduce P use efficiency but can reduce concerns related to water quality (Bundy, Andraski, & Powell, 2001; Smith, Harmel, Williams, Haney, & King, 2016), fertilizer placement may be a more important practical consideration for environmental outcomes that have no negative agronomic implications.

To determine opportunities for increasing P and K efficiency in corn–soybean rotations in the U.S. Midwest, it may be helpful to compare against benchmarks for other regions and cropping systems. The International Plant Nutrition Institute (IPNI, 2010) reported that PNB values of P and K averaged across the United States were 0.89 and 1.35, respectively, implying an efficiency that is two times greater than the averaged values in this study (Table 2). Dhillon et al. (2017) estimated that the global PNB value of P was 0.77 in cereal crops, which is 20% greater than those for corn in our study (Table 2). The lower values in our study might be attributed to the 4.5 times greater averaged P application rate (38.7 kg P ha^{-1} yr^{-1}) compared with the national averages on agricultural land (mean P fertilizer application, 8.62 kg P ha^{-1} yr^{-1}), even though the mean crop P removal (23.9 kg P ha^{-1} yr^{-1}) was approximately twice the national mean (11.98 kg P ha^{-1} yr^{-1}) (Metson, Lin, Harrison, & Compton, 2017). This comparison suggests a higher potential for nutrient losses to the environment in this region associated with P and K fertilization compared with the national scale. Little quantitative information is available for field-level P and K use efficiencies in this region, especially for AE and PFP. Therefore, our study contributes to the dataset of nutrient use efficiency parameters for systematic evaluation at a larger scale. For example, Syers et al. (2008) performed an analysis of long-term datasets for different regions of the world to help quantify future opportunities for improving P and K use efficiency, which is increasingly important amidst global concerns of P deficiency in soils and P scarcity to support agricultural production.

3.2 | Root growth and distribution in soil

Crop root distribution and morphology within the soil profile might have a key impact on crop nutrient uptake and consequently on crop production. Averaged across tillage/fertilizer placement and P and K rates at the IR position, a decrease in RLD was observed with each successive soil depth for corn (Figure 2a). Similarly, a significant decrease occurred for soybean roots below the 10-cm depth, and the decrease was greatest in the top 10 cm of the soil relative to the 10- to 30-cm depth increment (Figure 2c). For the BR positions, RLD was similar within the top 10 cm depth and decreased significantly for the 10- to 30-cm depth for both crops (Figure 2b,d). Although only a trend, the 5- to 10-cm depth had numerically greater (2.5 and 1.5 cm cm^{-3} for corn and soybean, respectively) RLD than the 0- to 5-cm depth. The MRD increased with soil depth increment in corn for both the IR and BR positions when averaged across tillage/fertilizer placement (Figure 3a). Greater RSD was observed at the 5- to 10-cm depth increment, with RSD being similar at the 0- to 5-cm and 10- to 30-cm depth increments (Figure 3b). The IR position had greater RLD than the BR position at the 5- to 10-cm depth increment for corn as well as greater MRD and RSD at all depths, demonstrating decreasing root density with increasing distance from the IR position, which was in line with observations from Li et al. (2017). Because soybean has a more sparse root system compared with fibrous-rooted crops like maize, RLD was markedly low in surface soil (0–10 cm) in both the IR and BR positions.

Regardless of position with respect to the crop row, RLD was significantly greater for NTBC within the top 10 cm of the soil relative to the strip-till treatments (STBC and STDB) for both crops except for BR position at the 0- to 5-cm soil depth for corn, but no differences existed in the 10- to 30-cm

TABLE 2 Treatment means and analysis of variance results for partial nutrient balance (PNB) for P and K, agronomic efficiency (AE), and partial factor productivity (PFP) in corn and soybean as affected by tillage/fertilizer placement or P and K fertilizer rate

	Corn				Soybean			
	PNB of P	**PNB of K**	**AE**	**PFP**	**PNB of P**	**PNB of K**	**AE**	**PFP**
Tillage placement (TP)[a]	kg P ha^{-1} removed (kg P ha^{-1} applied)$^{-1}$	kg K ha^{-1} removed (kg P ha^{-1} applied)$^{-1}$	kg ha^{-1} grain yield (kg ha^{-1} P/K applied)$^{-1}$	kg ha^{-1} grain yield (kg ha^{-1} P/K applied)$^{-1}$	kg P ha^{-1} removed (kg P ha^{-1} applied)$^{-1}$	kg K ha^{-1} removed (kg P ha^{-1} applied)$^{-1}$	kg ha^{-1} grain yield (kg ha^{-1} P/K applied)$^{-1}$	kg ha^{-1} grain yield (kg ha^{-1} P/K applied)$^{-1}$
NTBC	0.61a[b]	0.51b	7.9a	114.0b	0.42aa	0.79a	2.0a	33.7b
STBC	0.63a	0.54a	8.8a	120.6a	0.43a	0.79a	1.5a	34.9ab
STDB	0.611a	0.53ab	7.6a	118.4ab	0.44a	0.83a	2.0a	35.5a
PK fertilizer rate (PK)								
50	1.13a	0.98a	12.4a	218.8a	0.78a	1.50a	3.0a	64.9a
75	0.76b	0.65b	12.8a	150.4b	0.55b	1.04b	2.7ab	44.0b
100	0.58c	0.50c	7.3b	110.5c	0.41c	0.77c	1.7abc	32.7c
125	0.46d	0.39d	5.9b	88.5d	0.33d	0.62d	1.5abc	26.3d
150	0.41de	0.34de	5.3b	74.1de	0.28de	0.52de	1.1bc	21.8e
175	0.35e	0.29e	4.8b	63.8e	0.24e	0.45e	0.96c	18.6e
ANOVA ($P > F$)								
Source of variation								
TP	.394	.015	.857	.045	.436	.147	.196	.033
PK	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
TP × PK	.998	1.000	.996	1.000	.819	.859	.500	.789

Data are averaged over three sites and 8 yr (2007–2015).

[a]NTBC, no-till/broadcast; STBC, strip-till/broadcast; STDB strip-till/deep band.

[b]Same letters within a column and treatment parameter indicate no significant difference ($P > .05$).

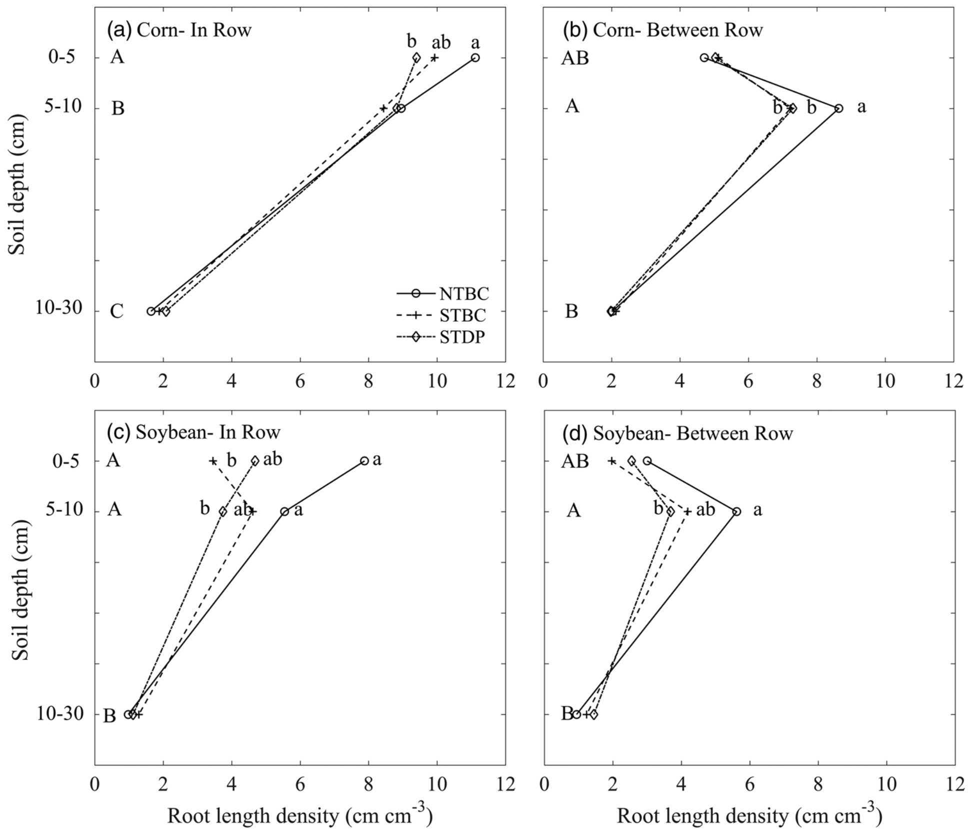

FIGURE 2 Three-year (2008–2010) root length density at the VT development stage for corn and the R1 stage for soybean as affected by soil depth and tillage/fertilizer placement treatment (no-till/broadcast [NTBC], strip-till/broadcast [STBC], and strip-till/deep band [STDB]). Panels are separated by crop (corn and soybean) and row position (in-row and between-row). Same uppercase letters indicate no significant difference between soil depths averaged over tillage/placement treatment. Same lowercase letters indicate no significant difference between tillage/placement treatments for a given depth ($P < .1$)

depth increment (Figure 2). At the 5- to 10-cm layer in both crops, NTBC system produced 19 and 52% greater RLD than STBC and STDB, respectively. Tillage/placement treatment differences in corn MRD were observed only in the top 10 cm of the soil. Averaged across row positions, the NTBC system had 4% greater MRD than STDB and 6% greater MRD than STBC (Figure 3a). Tillage/placement treatment differences in corn RSD were observed only in the 0- to 10-cm depth. Averaged across row positions, the NTBC system has 15% greater RSD than STDB and 21% greater RSD than STBC (Figure 3b). Similar MRD and RSD patterns were observed in soybean in 2009 (data not shown). The consistent response of root parameters to tillage/fertilizer placement practices agrees with prior studies (Farmaha et al., 2012a; Fernández & White, 2012; Li et al., 2017), indicating the presence of stressful conditions under NTBC, which influenced the depth of root growth. In contrast, Fernández et al. (2009) found that no-till practices might not be detrimental to soybean production because broadcast applications create a K-concentrated horizontal band that complements the natural morphological characteristic of the root system of soybean. However, in this study, root proliferation likely occurred as a compensatory mechanism in NTBC compared with STBC and STDB, which was indicated by the lowest yields in NTBC observed in both crops (Farmaha et al., 2012a).

3.3 | Long-term soil phosphorus and potassium levels

Over an 8-yr period when no P and K fertilizers were applied, the different tillage/fertilizer placement treatments produced similar declines in STP (−15 to −21 mg kg^{-1}) and STK test (−44 to −60 mg kg^{-1}) concentrations in the top 0- to 20-cm layer across the crop row positions (Figure 1). The STP and STK levels were fitted against time using linear models to derive incline/decline rates. The decline in soil test values in the top 0- to 10-cm layer with the unfertilized check were steepest relative to 10- to 20-cm and 20- to 30-cm depth increments, with slopes in the 0- to 10-cm layer ranging from −1.36 to −2.05 mg kg^{-1} yr^{-1} (R^2 = .28–.76; $p < .05$) for soil P test and from −3.91 to −7.01 mg kg^{-1} yr^{-1} (R^2 = .55–.87; $p < .05$) for soil K test (data not shown). Further, the decline rates in the top 0- to 10-cm layer in the unfertilized

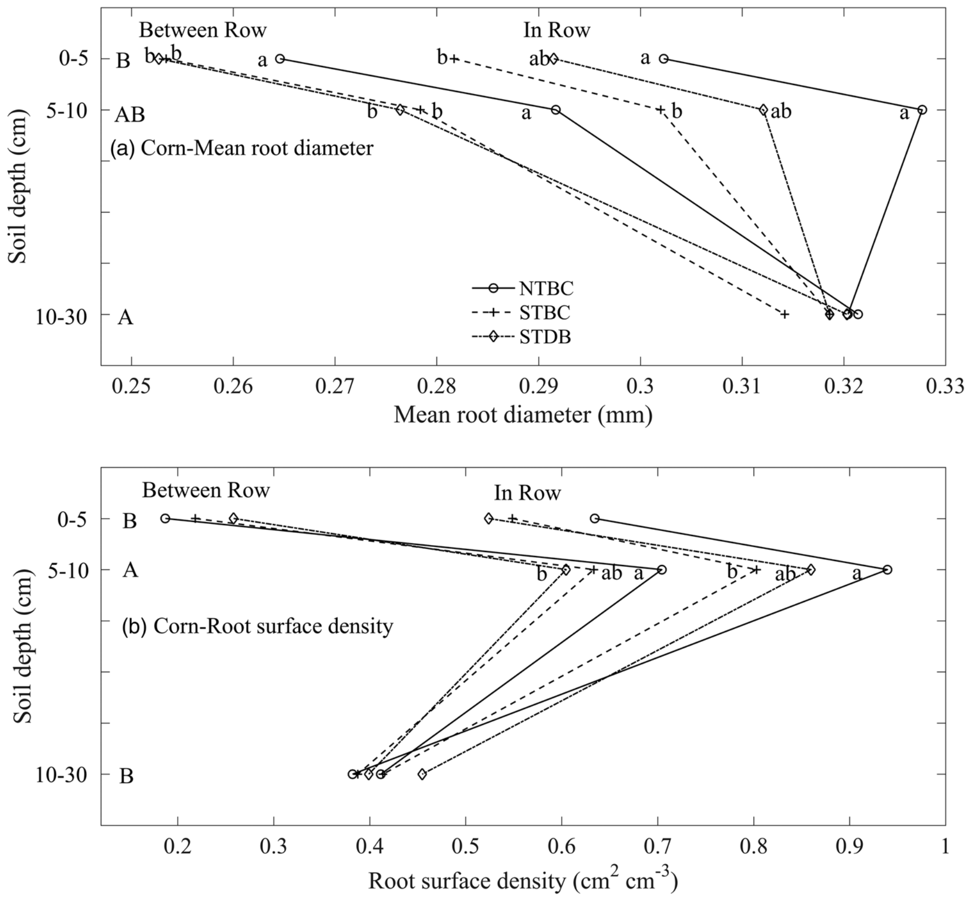

FIGURE 3 Two-year (2008 and 2010) mean root diameter (a) and root surface density (b) in corn at the VT development stage as affected by soil depth and tillage/fertilizer placement treatment (no-till/broadcast [NTBC], strip-till/broadcast [STBC], and strip-till/deep band [STDB]) for crop-row position (in-row and between-row). Same lowercase letters indicate no significant difference between tillage/placement treatments for a given depth ($P < .1$)

control were comparable for all sampling positions with respect to the crop row and the different tillage/fertilizer placement treatments (Supplemental Figure 1), suggesting similar crop nutrient uptake regardless of row positions and tillage systems. For the broadcast applications (NTBC and STBC), a pronounced buildup of STP and STK was found starting with the 125 kg PK ha^{-1} treatment (Supplemental Figure 1a,b). This increase was even greater with 175 kg PK ha^{-1}, where incline rates on the surface layer over the study period ranged from 1.2 to 7.0 mg kg^{-1} yr^{-1} for STP (R^2 = 0.46–0.56; $p < .1$) and from 3.71 to 4.60 mg kg^{-1} yr^{-1} for STK (R^2 = 0.25–0.46; $p < .1$) across the crop row positions.

Compared with the surface layer, declines in STP levels in subsurface layers were small for broadcast applications (NTBC and STBC) across the PK fertilizer rates and crop row positions (Supplemental Figure 1a,b). However, when fertilizer was applied in a subsurface band in STDB, STP levels at the 10- to 20-cm depth at the IR position increased by 7.0–60.5 mg kg^{-1} over the 8 yr (Supplemental Figure 1c), with incline rates ranging from 2.02 to 7.5 mg kg^{-1} yr^{-1} (R^2 = .28–.64) across the PK fertilizer rates. For the 20- to 30-cm depth increment, fertilizer rates >125 kg PK ha^{-1} in STDB also increased soil P test levels below the application band, which has been observed in prior studies (Fernández & Schaefer, 2012; Hansel et al., 2017). It is likely that the increase in soil P test levels in this location is the result of downward movement of P with the highest fertilization rate. In contrast to the IR position and similar to the broadcast treatments already mentioned, in STDB small declines in STP levels were detected at the three BR positions at the 10- to 20-cm and 20- to 30-cm depth increments. Soil K test levels also had small changes at the 10- to 20-cm layer with broadcast applications but increased by 14–130 mg kg^{-1} with fertilizer inputs in STDB (data not shown). For the 20- to 30-cm layer, STK concentrations generally increased across the PK rates and tillage/fertilizer placement treatments (data not shown). These results provide strong evidence that continuous broadcast applications of P and K over time above the buildup rate (i.e., 125 kg PK ha^{-1} in this study) have the potential to increase P and K test levels at the soil surface, and buildup rates at the soil surface increased significantly with increasing fertilizer rate. These results highlighted the importance of applying the right amount of P and K fertilizer because underapplication can lead to depletion of the soil nutrient at soil surface and constrain the optimum crop growth, and overapplication can result in excess buildup of STP and STK levels and associated reduction of return on fertilizer investment and potential environmental risks. In contrast, subsurface banding of fertilizers caused a substantial increase in P and K test levels in the location of the band instead of in the surface layer, without raising STP levels at soil surface even with the buildup rates. These trends were reported by other studies (Dodd & Mallarino, 2005; Farmaha et al., 2011, 2012a; Fernández & White, 2012; Hansel et al., 2017), indicating that deep placement of P fertilizer is beneficial to reduce the potential of surface P runoff (Yuan et al., 2018).

For the 0- to 10-cm and 10- to 20-cm layers receiving no P and K fertilizers, apparent P uptake (estimated by the change in nutrient content of the soil over time) was similar or slightly greater at the BR position than at the IR position for all tillage/fertilizer placement treatments (Supplemental Figure 1), despite the larger root parameters for IR compared with BR. This could be the result of younger and finer roots being at BR, which are the most active in nutrient and water uptake, although IR positions have more roots, which mainly serve with an anchor function (Farmaha et al., 2012a). These results emphasized the fact that, although with band applications the typical practice is to apply nutrients next to or below the planting row, the BR position may be more advantageous because the roots seem to be most active at taking nutrients there. Moreover, apparent P uptake was consistently greater on the surface layers than on the subsurface layers in our experiment, regardless of crop row position and tillage/fertilizer placement treatments. This finding agrees with Fernández and Schaefer (2012), indicating that, despite placement technique of P and K fertilizer, corn and soybean crops take up the majority of P from the soil surface layer. Of note is that apparent K uptake showed slightly different results, with BR being higher than IR for NTBC and STDB (data not shown), which was also observed and discussed at length by Fernández and White (2012). At the highest P and K rates applied in this study, STP levels were higher at the BR than IR positions for broadcast applications at all depths (Supplemental Figure 1), which may be a result of greater cycling of nutrients over time into this position as crop residue accumulates into BR during strip-till and planting operations. In contrast to soil P dynamics, higher soil K test levels were observed at the IR positions than at the BR positions (data not shown), which is the result of substantial K leaching from plant materials between physiological maturity and harvest when the crop is planted always in the same place, as has been reported by others (Fernández & Schaefer, 2012; Howard, Essington, & Tyler, 1999; Mallarino & Borges, 2006).

Linear models were fitted between the means of STP and STK for all four row positions against time for the seven P and K rates (Figure 1). Soil test P levels decreased linearly when P rates were <50 kg P ha^{-1} and started to increase with greater P fertilizer additions (Figure 1a). A similar trend was found in soil test K levels, with a threshold value for maintaining soil test K levels near the 100 kg K ha^{-1} treatment (Figure 1b). Maintenance rates for STP and STK were determined as 56 kg P ha^{-1} and 105 kg K ha^{-1}, respectively, which were comparable to the current recommendations in Illinois Agronomy Handbook (Fernández & Hoeft, 2009).

Frequent reevaluation of critical STP and STK concentrations, above which fertilization no longer results in yield responses or economic benefits, is important to ensure adequate P and K supply to crops as environments, genetics, and management practices change. Although current recommendations for Illinois are based on 18-cm-deep samples (Fernández & Hoeft, 2009), our study evaluated crop response with 20-cm-deep samples. Although sampling depth is important, especially in conservation tillage systems where P and K tend to accumulate near the soil surface (and where uptake seems to be most dynamic as previously described), others have found little benefit in reducing sampling depth to improve nutrient uptake predictions for conservation tillage systems (Borges & Mallarino, 2000; Fernández, Brouder, Beyrouty, Volenec, & Hoyum, 2008). The likelihood of corn response to P and K was low when STP was >21–46 mg P kg^{-1} and STK was >148–272 mg K kg^{-1}, and soybean was not likely to respond to P and K when STP was >19–32 mg P kg^{-1} and STK was >154–544 mg K kg^{-1} (Table 3). In this study, the large discrepancy in critical values for STP and STK in both crops was dependent on the selected models. The determined critical soil concentrations were significantly greater ($P < .05$) using the exponential (EXP) model than those derived from linear plateau (LP) and QP models for both crops. It has been concluded that the EXP model generally provided the highest values relative to other models (Dodd & Mallarino, 2005; Khan et al., 2018). Compared with current university-recommended values of STP (20 mg P kg^{-1}) (Fernández & Hoeft, 2009), the critical concentrations determined in this study were comparable if using LP or QP models but were 44–79% greater if using EXP model. For the current critical values of STK (150 mg K kg^{-1}), the determined value was similar if using the LP model but was 12–36% higher using QP model and 72–113% higher using the EXP model (Table 3). Using the QP model, given the fact that current recommendations in Illinois as well as many other states within the corn belt use QP models, the critical level for STP observed in our study was consistent with the current university recommendation, while the values for STK are slightly greater. This trend illustrates the need to continue to re-evaluate

TABLE 3 Regression models for relationships between relative grain yield and soil-test P and K for corn and soybean across the sites and determined critical soil-test concentrations

Crop	Model[a]	Soil test P Equation	R^2	CC[b] mg P kg^{-1}	Soil test K Equation	R^2	CC mg K kg^{-1}
Corn	LP	$33.8 + 4.57x$ for $x < 20.9$	.54	20.9	$-10.1 + 0.73x$ for $x < 147.9$	.77	147.9
	QP	$18.1 + 8.2x - 0.198x^2$ for x < 20.9	.52	20.9	$-84.8 + 2.1x - 0.0062x^2$ for $x < 172.1$	.80	172.1
	EXP	$121.4 - 108.5e^{-0.097x}$	.52	46.2	$107.4 - 334.3e^{-0.021x}$	.79	272.8
Soybean	LP	$56.0 + 2.62x$ for $x < 19.1$	.43	19.2	$8.3 + 0.59x$ for $x < 153.9$	.54	153.9
	QP	$35.2 + 6.31x - 0.149x^2$ for $x < 21.2$	.45	21.2	$-33.9 + 1.31x - 0.0030x^2$ for $x < 217.5$	.53	217.5
	EXP	$107.6 - 98.5e^{-0.143x}$	.45	31.5	$143.3 - 184.3e^{-0.0089x}$	.52	544.6

[a]LP, linear plateau; QP, quadratic plateau.
[b]CC, critical soil-test concentration.

recommendations to remain relevant for current production systems and technologies. The current university-recommended critical P and K levels in Illinois are based on work conducted during the 1960s. Obviously, much has changed since this set of recommendations was established, not only in terms of yield but also in terms of other factors such as economics, greater awareness of environmental sustainability, hybrids, nutrient distribution and nutrient status of the soil, climate, and management. Although this 8-yr study focused on conservation tillage systems at only three on-farm trials in east-central Illinois, these results suggest that re-evaluating current recommendations for soil P and K critical concentrations in the state of Illinois are warranted to support crop production for current high-yielding corn and soybean crops. To accomplish this, further studies are needed across a larger gradient of soil types, tillage practices, and crop production systems to develope improved recommendations. Furthermore, current recommendations were solely based on productivity level. As additional work is done to re-evaluate recommendations, emphasis should be given also to environmental stewardship to ensure an adequate balance between production and environmental protection goals. As highlighted in this study, P rate and placement could have important roles in reducing soil P concentrations in surface layers, and, as mentioned in a related study (Yuan et al., 2018), reduce the potential for P runoff.

4 | CONCLUSIONS

Averaged across 8 yr and three sites, STBC and STDB produced the highest yield in corn (by 6.2 and 4.5%) and soybean (by 3.1 and 6.1%), respectively, relative to NTBC, which consistently resulted in the lowest yields in both crops. This study showed a yield benefit with strip-till over no-till, but an advantage of subsurface banding relative to broadcast practices within strip-till was not observed at different PK fertilizer rates, possibly due to sufficient soil nutrient levels at the start of these experiments. The lowest yield in NTBC was consistent with larger RLD at both the IR and BR positions, implying stress conditions with this tillage/fertilizer placement treatment that likely induced greater allocation of photosynthetic to roots instead to grain yield. Three parameters of PUE and KUE assessed in this study were significantly affected by conservation tillage and P and K rates, but no advantage of deep banding practice for increasing nutrient use efficiency was found compared with broadcast practice. The averaged PNB values of P and K in this study were ∼50% of the national means, mainly due to the higher mean P and K fertilizer inputs. The addition of field-level datasets of PUE and KUE parameters for this system could help set benchmarks for comparison against other regions when determining opportunities for increasing nutrient use efficiencies in high-yielding crop production systems. Broadcast applications yielded significant buildups of STP and STK levels at soil surface layers over an 8-yr period, highlighting the potential for negative water quality outcomes with excessive surface P and K fertilization. Meanwhile, subsurface banding P and K caused substantial increases in soil test P and K levels at the point of fertilizer application instead of at the surface layer, suggesting that deep placement of P fertilizer is beneficial to reduce the potential for surface nutrient losses. Using the QP model, the critical value of STP (21 mg P kg^{-1}) was comparable to the recommended value (20 mg P kg^{-1}), whereas the values of STK (217 mg P kg^{-1}) were greater than the current value (150 mg K kg^{-1}). The determined P and K maintenance rates in this study are an important first step locally in the re-evaluation of current university-based recommendations, but at a global scale highlight that recommendations are not static and should be re-evaluated periodically to ensure they correctly represent current conditions and approaches to nutrient management.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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