Assessment of Soil Phosphorus and Potassium following Real Time Kinematic-Guided Broadcast and Deep-Band Placement in Strip-Till and No-Till

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Fertilizer placement may cause non-uniform nutrient distribution in the soil, making it difficult to determine whole-field fertility by traditional sampling strategies. Our objectives were to determine P and K distribution after repeated applications in no-till and strip-till soils and to develop improved sampling procedures to estimate soil P and K levels on a corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation with crops planted at 76-cm row spacing. Three trials near Pesotum, IL, received blends of 0–0, 22–42, 33–62, 44–83, 55–104, 66–125, and 77–145 kg P–K ha^{-1} in fall 2007 and 2009 before corn planting. Applications were broadcast-applied in no-till (NTBC) and strip-till (STBC) and deep-banded in strip-till (STDB) 15 cm below the surface in the crop row (IR) using real-time kinematic (RTK) satellite navigation. Every year soil P and K was measured at 10-cm increments to a 30-cm depth at 0, 19, 38, and 57 cm from the IR. Subsurface banding reduced P and K levels in the surface and increased them at the point of application, or deeper with the highest rate, while broadcast applications increased surface levels. Soil-surface K levels were greater at IR likely because of K leaching from senescing standing crops. Soil-test results indicated no need to adjust fertilizer rate based on tillage or fertilizer placement. A sampling ratio of 1:3 IR to between the crop rows (BR) seemed adequate to estimate soil fertility across a wide range of P- and K-fertilizer rates and soil test levels where the location of the fertilizer band or planting row is maintained constant.

Abbreviations: BR, between the crop rows; IR, in the crop row; NTBC, no-till/broadcast; RTK, real-time kinematic; STBC, strip-till/broadcast; STDB, strip-till/deep-band.

No-till corn and soybean production has become more widely accepted over the last 20 yr because, among other factors, it can represent savings in operation cost and may conserve soil and water resources to a greater extent than conventional tillage systems. However, new technologies that increase corn plant densities and reduce pest damage to plant materials have resulted in larger amounts of undecomposed crop residue remaining by spring time on the soil surface of no-till systems. Besides the mechanical interference with planting operations, soils covered with crop residue tend to stay wetter and cooler longer. These conditions can delay planting, germination, and early crop growth compared to conventional tillage systems (Vetsch and Randall, 2002). In recent years, strip-till has emerged as an alternative system as it incorporates the benefits of soil and water conservation of no-till and the improved seedbed conditions of conventional tillage (Morrison, 2002). Improved seedbed conditions with strip-till have resulted in enhanced crop growth and yield (Morrison, 2002; Randall and Vetsch, 2008; Farmaha et al., 2011).

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Strip-till allows for simultaneous deep banding of fertilizers. Deep banding of slowly mobile nutrients, such as P and K, has been proposed as an alternative to improve nutrient availability, fertilizer use efficiency, and yield (Hairston et al., 1990; Bordoli and Mallarino, 1998; Ebelhar and Varsa, 2000; Borges and Mallarino, 2000, 2003). However, others have observed no or small benefit to deep-banding relative to broadcast applications (Hudak et al., 1989; Yin and Vyn, 2002a, 2002b; Borges and Mallarino, 2003; Rehm and Lamb, 2004; Farmaha et al., 2011). Nonetheless, when repeated broadcast applications of P have caused high levels of this nutrient in the soil surface, deep banding may help reduce such levels and lower the potential for environmental degradation associated with P runoff from fields (Sharpley and Halvorson, 1994; Duiker and Beegle, 2006; Randall and Vetsch, 2008; Farmaha et al., 2012). Conversely, a potential drawback is that the soil disturbance created with strip-till during deep banding of P could actually increase the potential for P loss by soil erosion compared to no-till systems. Regardless of whether or not deep-banding P and K fertilizer is beneficial, there is consensus that deep banding creates a challenge when soil sampling to try to accurately represent soil P and K test levels of a field (Kitchen et al., 1990; Tyler and Howard, 1991; Rehm et al., 1995; Varsa and Ebelhar, 2000; Rehm and Lamb, 2004; Mallarino and Borges, 2006).

Since crops do not usually take up all of the P and K applied in a band, the residual fertilizer creates a zone of concentrated nutrients (Miner and Kamprath, 1971; Farmaha et al., 2012). While succeeding crop removal and chemical transformations that render P and K less available to plants can reduce the amount of residual fertilizer, soil P and K test levels normally remain high for a prolonged period of time. Perpetuation of a horizontal pattern of high and low levels across the field is most likely to occur with strip-till because this system is designed to maintain strips in the same location and provide a controlled-traffic system. In recent years the use of RTK satellite navigation technology makes it possible to plant and band fertilizers always in the same location, which can also intensify the formation of fertilizer patterns in the field. One of the goals of soil sampling is to use a sampling area to represent a larger area and assess soil test levels to determine fertilizer needs of crops (Peck and Soltanpour, 1990). However, it is well recognized that one of the most important sources of error in assessment of fertility levels is the way in which soil samples are collected (Petersen and Calvin, 1996). When nutrients are banded, representing the fertility of the field can be difficult even when the location of the fertilizer band is known. For example, in a 76-cm band spacing system Kitchen et al. (1990) indicated that for each sample collected in the fertilizer band 20 samples outside the band were needed to accurately represent soil P test levels. Others have indicated that random sampling when a fertilizer band is present requires anywhere from 15 to 30 samples to accurately represent the fertility of a field (Hooker, 1976; Shapiro, 1988). Further, Hooker (1976) indicated that 100 randomly collected cores are needed to substantially reduce variability in measurements when a P band is present. When the location of the band is unknown and <20 subsamples are taken, Kitchen et al. (1990) suggest a paired sampling approach by collecting the first sample at a random location and the second sample perpendicular to the band direction at a distance from the first sample equal to half the band-spacing.

A number of studies have shown the distribution of P and K levels in the soil after broadcast and banded fertilizer applications for no-till, ridge-till, chisel-plow, and chisel-disk (Kitchen et al., 1990; Tyler and Howard, 1991; Rehm et al., 1995; Howard et al., 1999; Varsa and Ebelhar, 2000; Borges and Mallarino, 2001, 2003; Rehm and Lamb, 2004; Mallarino and Borges, 2006; Farmaha et al., 2012). Relatively less is known about the distribution of soil P and K test level under strip-till. A study by Farmaha et al. (2012) described the distribution of soil P and K test level with deep-banding in strip-till. However, their study did not include broadcast applications for strip-till. Despite the fact that most of the above-mentioned studies have recognized the difficulty of obtaining a sample that accurately represents the fertility of a field with banded fertilizer, still the best way to collect such samples is poorly understood. Further, to our knowledge no study has been designed to improve soil sampling strategies to assess soil P and K test levels in strip-till fields. Therefore, the objectives of this study were to (i) determine the distribution of soil P and K test levels after repeated applications of various P and K rates in NTBC, STBC, and STDB and (ii) develop soil sampling procedures to improve estimation of soil P and K test levels.

MATERIALS AND METHODS

Site Description

The study was conducted in commercial fields during 2007 to 2010 at three locations near Pesotum, IL, (East Central Illinois). The three fields were near each other, approximately within a 2 km radius. Soils in all three sites were a combination of Drummer silty clay-loam soil (fine-silty, mixed, superactive, mesic Typic Endoaquoll) and Flanagan silt loam (fine, smectitic, mesic Aquic Argiudolls). Each of these sites had no prior history of banded fertilizer placement and fields were chisel plowed after corn and field cultivated after soybean in years before the study. Soil analysis of composite samples collected from the top 18-cm layer showed organic matter ranged from 30 to 35 g kg^{-1} across sites, cation exchange capacity ranged from 17 to 30 $cmol_c$ charge kg^{-1}; and pH (1:1 soil/water ratio) ranged from 5.1 to 6.3. Except for tillage and P and K fertilization, the crops were managed as recommended for the region.

Treatments

The study was conducted on a corn–soybean rotation with 76-cm row spacing in all sites and for both crops. All three sites had soybeans during the 2007 growing season before the start of the study, thus corn was the first crop planted after treatment establishment. Plot size was 6 by 150 m and treatments remained in the same plot for the duration of the study. The study was set up as a split-plot arrangement in a randomized complete-block design with two replications. The main (whole) plot included three tillage/fertilizer placement treatments: no-till/broadcast (NTBC); strip-till/broadcast (STBC); and strip-till/deep-band (STDB). The split-plot treatments were blends of P and K made to create seven P–K fertilizer treatments with a control receiving no P or K (0–0 or check). The six additional rates were established in 25 kg P_2O_5 and K_2O ha^{-1} increments starting with a blend of 50 kg P_2O_5 ha^{-1} and 50 kg K_20 ha^{-1} to produce P–K blended rates of 22–42, 33–62, 44–83, 55–104, 66–125, and 77–145 kg P–K ha^{-1}. We established these rates to ensure a distribution of fertilizer rates above and below P and K removal levels. Three consecutive corn–soybean cropping years before our study (2002–2007) (mean corn yield of 10.0 Mg ha^{-1} and mean soybean yield of 3.3 Mg ha^{-1}) and recommended removal rates (Fernández and Hoeft, 2009) were used to estimate P and K removal levels for our study.

Strip-till operations were done always in the fall and corn was planted on the location of the strips the following spring. The soybean crop was also planted on the same crop-row position as corn but no tillage operations were performed for soybean. The location of the tillage and the banded fertilizer was maintained constant by using RTK satellite navigation technology (±2.5-cm accuracy) (Trimble Field Manager Software) with two GPS receivers, one mounted on the tractor and the other mounted on the tillage bar. Strip-till was performed on 76-cm row spacing using a strip-till toolbar (DMI, Model 4300) consisting of vertical coulters and row cleaners in front of knifes designed for dry fertilizer application and closing disks behind the knives to cover the knife slit with soil and form a residue-free berm approximately 5- to 8-cm tall and 25-cm wide. The strip-tillage operation disturbed the soil to approximately 17- to 19-cm deep. There was no soil disturbance before planting in the NTBC treatment.

Fertilizer treatments were also applied every 2 yr in the fall before corn planting starting in fall 2007. Broadcast applications were done with a drop spreader (10T Series, Gandy, Owatonna, MN). 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, Gandy, Owatonna, MN). Fertilizer sources were diammonium phosphate (DAP) (18–46–0) in 2007 and triple superphosphate (TSP) (0–45–0) in 2009 as the P source, and KCl (0–0–60) as the K source. For the 2008 corn crop corrective N rates were applied to offset the N content of DAP fertilizer. All corn plots received a total of 200 kg N ha^{-1}. To minimize variability, the same equipment and operator were employed to perform strip-tillage and nutrient placement at all three locations.

Measurements

Soil samples for P and K analysis were collected from each plot every fall after crop 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. A composite of 12 soil cores (2-cm diam. each) was made for each of four positions with respect to the crop row: IR and BR 19, 38, and 57 cm from the IR. These BR positions will be referred to as BR-19, BR-38, and BR-57. Each sample was partitioned into 0- to 10-, 10- to 20- and 20- to 30-cm depth increments. The composite 12 soil-core samples were collected three per each of the positions with respect to the crop-row within a four-row geo-referenced 3 by 3 m area in the center of each treatment. To ensure consistency in the sampling position with respect to the crop row, a board with pre-drilled holes at the designated distances was used. Soil samples were air dried, ground to pass through a 2-mm diam. sieve, and analyzed for P and K with the Mehlich-III extraction and analyzed with a spectrophotometer for P (Frank et al., 1998) and with an atomic absorption spectrometer for K (Warncke and Brown, 1998).

Most P and K fertilizer recommendations in the Midwest are based on no more than 20 cm of soil depth (Vitosh et al., 1996; Fernández and Hoeft, 2009). Following this approach, we created a soil P and K test weighed average for the top 20 cm of the soil for the different tillage/fertilizer placement and fertilizer rate treatments. To determine whole-field test levels, the top 20-cm soil P and K test levels were then used to calculate soil test levels for different sampling scenarios created by various ratios of IR to BR cores: 1:3, 1:2, 1:1, 1:0, 0:3. The 1:2 and 1:1 ratios were calculated from the average of all possible combinations of IR and the appropriate number of BR samples drawn from a population of three BR samples. All these calculated test levels were compared to calculated "true" mean soil test levels for each fertilizer rate treatment. The true mean soil test level for the top 20 cm of soil was defined as the value obtained when averaging across the test values from one sample collected at IR and three samples collected at BR (1:3 ratio of IR/BR cores) for the NTBC treatment. This approach to calculate the true mean was deemed appropriate because pre-treatment (starting conditions) soil P and K test levels in 2007 for each individual sampling position with respect to the crop row and averaged across sampling position with respect to the crop row for the top 20 cm of the soil were similar for the different treatments. Also, since the effect of broadcast P and K applications in no-till systems is already well documented, this system would represent an appropriate standard on which to compare other less-defined systems. The 1:3 sampling rate for the true mean represents the most complete set of cores collected. Since banding creates the same pattern across the field and one of the objectives of soil sampling is to use a sampling area to represent a larger area (Peck and Soltanpour, 1990), it follows that using a systematic approach that accounts for one complete pattern or multiples of it should fulfill this objective. In our study the sampling approach systematically divided the 76-cm banding pattern into four 19-cm wide quarters.

Statistical Analysis

Data were analyzed with the MIXED procedure of SAS (SAS Institute, 2009). Year and block and their interactions with treatments were considered random effects. The year × location interaction had very small variation for soil P and K test levels compared to the year × location × block interaction, thus only the latter interaction was included in the model as a random effect. The fixed effects were tillage/fertilizer placement, fertilizer rate, position with respect to the crop row and soil depth. Observations were treated as independent (rather than repeated) measurements because there were no significant correlations between the observations. The LS Means for significant fixed effects were further analyzed by obtaining F tests for simple effects (partitioning F tests of a variable at each level of another variable of interest) by the SLICE option in the PROC MIXED procedure of SAS (SAS Institute, 2009). The SLICE option was also used to analyze the change in soil P and K test levels between the start of the experiment and 2010 at each level of the fixed effects. In this analysis, year was also considered a fixed effect. Finally, the SLICE option was used to compare soil P and K test levels of different sampling scenarios to the true mean.

RESULTS AND DISCUSSION

While seed yield response to treatment was not the focus of this study, we briefly present this information as it relates to nutrient removal, which can influence changes in soil P and K levels. Corn seed yield (2-yr mean) was 11.4 Mg ha^{-1}for the NTBC treatment and lower ($P < 0.1$) than 12.0 Mg ha^{-1}for STBC and 11.8 Mg ha^{-1}for STDB. No other significant treatment or treatment interactions were observed (data not shown). Mean soybean yield was 3.0 Mg ha^{-1} and there were no treatment differences. Similarly, there were no treatment effects on seed P and K concentrations and mean nutrient concentrations in corn seed were 2.26 g P kg^{-1} and 3.46 g K kg^{-1}, while nutrient concentrations in soybean seed were 6.54 g P kg^{-1} and 20.0 g K kg^{-1}. Removal of P and K in seed over the 3-yr period of this study (2 yr of corn and one of soybean) were not affected by tillage/fertilizer placement treatment, but there was a linear increase in nutrient removal in seed with P fertilizer rate [kg P ha^{-1} removal = 19.037 + (0.0355 × P rate); $R^2 = 0.63$; $P < 0.001$] and with K fertilizer rate [kg K ha^{-1} removal = 38.334 + (0.0225 × K rate); $R^2 = 0.50$; $P < 0.086$]. We calculated mean annual removal rates of 21 kg P ha^{-1} (range = 19–22 kg P ha^{-1}) and 40 kg K ha^{-1} (range = 38–41 kg K ha^{-1}). Since these values were nearly equivalent to the biennial fertilizer rate of 44 to 83 kg P–K ha^{-1}, we selected this rate to represent the maintenance fertilizer rate for our study.

Averaged across location and treatments, starting soil test levels in 2007 were 30, 13, and 8 mg P kg^{-1} and 189, 123, and 116 mg K kg^{-1} for the 0- to 10-, 10- to 20-, and 20- to 30-cm depth increments, respectively. The degree of vertical stratification in soil test levels was greater for P than K. For P the ratio of surface (0–10 cm) to subsurface test levels was 2.2:1 for the 10- to 20-cm depth increment and 4.0:1 for the 20- to 30-cm depth increment. For K the ratio of surface (0–10 cm) to subsurface test levels was 1.5:1 for the 10- to 20-cm depth increment and 1.6:1 for the 20- to 30-cm depth increment. This large degree of vertical stratification was likely the result of broadcast applications with minimal disturbance of the soil by tillage before this study. Even with chisel-plow (the most aggressive soil-mixing tillage implement used before the study) it would be expected that broadcast P and K fertilizers would become stratified in the soil (Holanda et al., 1998).

Evaluation of soil P and K test levels averaged over years and locations showed most interactions and all main effects were significant (Table 1). For soil P and K test levels, the tillage/fertilizer placement × fertilizer rate × position with respect to the crop-row was explained by increased soil P and K test levels at IR as fertilizer rate increased for STDB compared to the broadcast treatments (NTBC and STBC). For the highest fertility treatment at IR, soil P test levels for the 0- to 30-cm depth increment in STDB were 32 mg P kg^{-1} and 45% greater than levels in STBC and 88% greater than levels in NTBC. Similarly, for the highest fertility treatment at IR, soil K test levels for the 0- to 30-cm depth increment in STDB were 177 mg K kg^{-1} and 13% greater than levels in STBC and 20% greater than levels in NTBC. The increase in soil P and K test levels was the result of localized fertility with the fertilizer band and agrees with other studies (Tyler and Howard, 1991; Mallarino and Borges, 2006). This increase is likely caused by residual fertilizer because crops normally do not take up nutrients exclusively from the fertilizer band (Farmaha et al., 2012).

A significant tillage/fertilizer placement × fertilizer rate × soil depth interaction (Table 1) indicated that soil P test levels increased as fertilizer rate increased in the 0- to10-cm depth increment of the broadcast treatments (NTBC and STBC) but no differences occurred for the STDB treatment. Conversely, with increasing fertilizer rates soil P test levels increased in the 10- to 20-cm depth increment of STDB but no changes occurred for the broadcast treatments. The increase in soil P test levels at the soil surface, especially when P applications exceed seed removal by the crop, is a well-recognized effect of broadcast applications (Shear and Moschler, 1969; Mackay et

Table 1. Analysis of variance for soil P and K test levels averaged over 4 yr (2007–2010).

Source of variation	df†	Soil P		Soil K	
		F	$P > F$	F	$P > F$
Tillage/fertilizer placement (T)	2	34.90	0.001	10.42	0.001
Fertilizer rate (F)	6	19.37	0.001	30.20	0.001
T × F	12	8.89	0.001	12.67	0.001
Position with respect to the crop row (P)	3	22.54	0.001	241.13	0.001
T × P	6	57.17	0.001	18.85	0.001
F × P	18	4.55	0.001	3.76	0.001
T × F × P	36	3.23	0.001	1.65	0.008
Soil depth (D)	2	1934.02	0.001	4372.26	0.001
T × D	4	71.06	0.001	18.27	0.001
F × D	12	3.93	0.001	7.11	0.001
T × F × D	24	3.97	0.001	1.25	0.185
P × D	6	21.21	0.001	51.90	0.001
T × P × D	12	12.72	0.001	1.37	0.174
F × P × D	36	1.24	0.153	0.71	0.903
T × F × P × D	72	1.04	0.379	0.48	0.999

† Numerator degrees of freedom from Type III sum of squares.

al., 1987; Holanda et al., 1998; Mallarino and Borges, 2006). Results for deep banding of P also illustrate the possibility to reduce soil surface P test levels while increasing them at the subsurface. Others have observed similar results and indicated that deep banding of P can be a beneficial practice to reduce soil surface P test levels and hypothesized that it can lower the potential for P runoff (Randall and Vetsch, 2008; Farmaha et al., 2012). The tillage/fertilizer placement × position with respect to the crop-row × soil depth interaction further showed the observed increase in subsurface soil P test levels occurred only at the location of the fertilizer band. The STDB treatment produced a twofold increase in soil P test levels within the IR at the 10- to 20-cm depth increment relative to the broadcast treatments. Our results agree with others indicating that subsurface banding of fertilizers can result in highly localized fertility (Kitchen et al., 1990; Tyler and Howard, 1991; Mallarino and Borges, 2006).

For soil K, the two-way interactions tillage/fertilizer placement × soil depth (Table 1) was explained by greater soil K test levels in the 0- to10-cm depth increment of the broadcast treatments (NTBC and STBC) than the STDB treatment. Conversely, soil K test levels were higher for STDB in the 10- to 20-cm depth increment compared to the broadcast treatments. While these results may illustrate the possibility to reduce soil surface K test levels and increase them at the subsurface with deep banding of K, in all cases differences between tillage/fertilizer placement were small (<7 mg K kg^{-1}) and likely amount to little practical advantages. The fertilizer rate × soil depth interaction showed that increasing fertilizer rates from 0 to 145 kg K ha^{-1} increased soil K test levels by 23 mg K kg^{-1} in the soil surface but little change occurred in the subsurface. Further, the position with respect to the crop-row × soil depth interaction showed that most of the observed increase in soil K test levels in the 0- to 10-cm depth increment occurred at the IR position. The increase in soil K levels at the surface was likely the combined effect of broadcast applications and crop cycling of K from the soil subsurface to the surface. Plant cycling of K at the IR position has been observed by others as well (Tyler and Howard, 1991; Howard et al., 1999; Varsa and Ebelhar, 2000).

The differences described in the statistical analysis of main effects and interactions were more easily recognized and better explained in certain instances by measuring the change in soil P and K test levels resulting from the treatments over time. For simplicity we only show three fertility levels representing the check (0–0 P–K kg ha^{-1}), a maintenance rate (44–83 P–K kg ha^{-1}), and a buildup rate (highest fertility rate) (77–145 P–K kg ha^{-1}) for a corn–soybean cropping system following state recommendations (Fernández and Hoeft, 2009). Similar decline in soil P and K test levels at the top 10-cm of the soil were observed for the unfertilized check for all sampling positions with respect to the crop-row and the different tillage/fertilizer placement treatments; but no change occurred in the 10- to 20- and 20- to 30-cm depth increments (Fig. 1A and 2A). The decline observed only in the soil surface is likely related to crop removal as these fields had <2% slope and nutrient loss by runoff is unlikely. These data agree with other studies that indicate crop nutrient uptake occurs mostly on the surface layer of the soil (Fernández et al., 2008, 2009; Farmaha et al., 2012).

At the maintenance P fertilizer rate (44 kg P ha^{-1}), there was no change in soil P test levels for the broadcast treatments (NTBC and STBC) across all sampling positions with respect to the crop-row for the top 30 cm of the soil (Fig. 1B). These results agree with P removal rates measured in seed and illustrate that the current P maintenance rate recommendations (Fernández and Hoeft, 2009), developed under conventional tillage systems, are adequate for broadcast applications under conservation tillage systems. For the STDB treatment there was an 80 mg P kg^{-1} increase in soil test levels at the IR position within the 10- to 20-cm depth increment. This increase was the result of localizing a maintenance rate on a small portion of the soil volume. Just as with the unfertilized check, soil P test levels in STDB decreased at the surface layer for all BR positions. This finding agrees with Farmaha et al. (2012) and likely indicates that despite placement technique corn and soybean crops take most of their P from the soil surface layer. These data further indicate that continuous band application of P in the same location can result in substantial localized increase in soil P test levels and depletion in the rest of the root zone. We observed this increase even at the lowest P rate of 22 kg P ha^{-1} where soil P test levels at IR in the 10- to 20-cm layer of STDB increased 19 mg P kg^{-1} between the start of the study in fall 2007 and fall 2010 ($P = 0.011$).

At the highest P fertilizer rate (77 kg P ha^{-1}), soil P test levels increased at the soil surface of the broadcast treatments at most sampling positions with respect to the crop row (Fig. 1C). This increase was expected as the fertilizer rate exceeded the measured annual 21 kg P ha^{-1} removal rate in seed. Averaged across sampling position with respect to the crop row, the highest fertilizer rate treatment increased soil surface P test levels for the NTBC treatment by 11 mg P kg^{-1} ($P = 0.029$) and for the STBC treatment by 15 mg P kg^{-1} ($P = 0.003$), whereas soil surface P test levels decreased by 11 mg P kg^{-1} for the STDB treatment ($P = 0.036$). Similar to the maintenance rate, P levels increased by 73 mg P kg^{-1}in STDB at IR in the 10- to 20-cm depth increment as a result of the band application of 77 kg P ha^{-1}. However, with the highest P rate we observed an increase in soil P test levels below the application band in the 20- to 30-cm depth increment. 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. Another possibility for the increase in test levels at the 20- to 30-cm depth at IR for STDB is deeper-than-expected fertilizer applications. However, this is unlikely because as with the maintenance rate (44 kg P ha^{-1}) the 20- to 30-cm depth increment had no significant changes in P levels for the 22, 33, and 55 kg P ha^{-1} rates (data now shown). On the other hand, as with the 77 kg P ha^{-1} rate, there was a significant 22 mg P kg^{-1} increase in the 20- to 30-cm depth increment with the 66 kg P ha^{-1} rate; further indicating that downward P movement in STDB was the result of high P application rates. Others have observed downward P movement

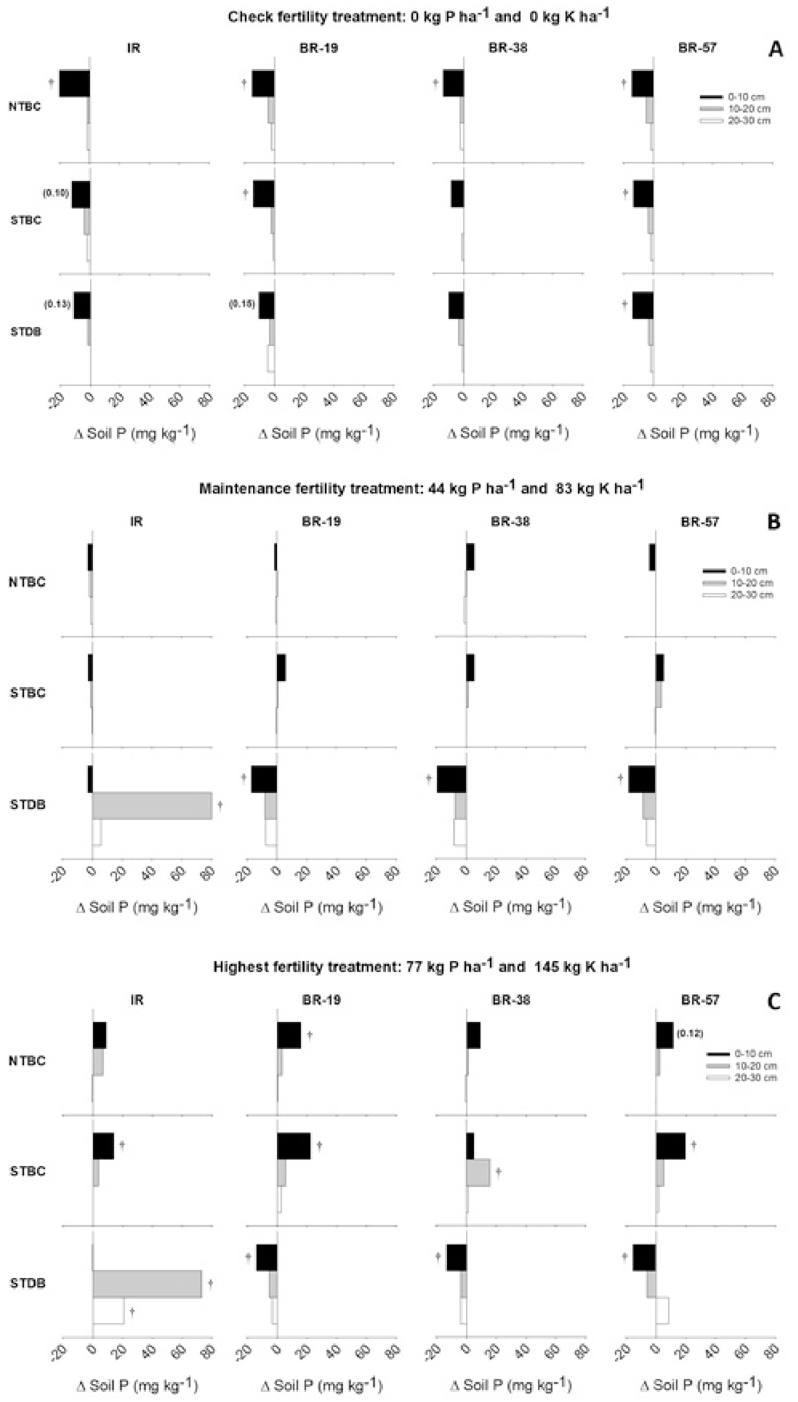

Fig. 1. Change in mean soil P test level from pre-treatment levels in 2007 to fall 2010 at various soil depth increments for different positions with respect to the crop row (in the crop row [IR] and between the crop rows [BR] 19, 38, and 57 cm from the IR) for no-till/broadcast (NTBC), strip-till/broadcast (STBC), and strip-till/deep-band (STDB) tillage/fertilizer placement treatments and three fertilizer rates (graphs A, B, C). †Indicate significant differences at $P < 0.1$; actual probability indicated between parenthesis for $0.15 \geq P \geq 0.1$.

in similar soils with high P test levels created by fertilization (Sims et al., 1998).

Change in soil K test levels at IR for STDB treatments receiving K fertilizer (Fig. 2B and 2C) showed similar results to those of P. Application of K fertilizer in a concentrated band produced a large increase in soil K test levels at the 10- to 20-cm depth increment. For the maintenance rate (83 kg K ha^{-1}) the increase was 43 mg K kg^{-1} while for the highest rate (145 kg K ha^{-1}) the increase was 85 mg K kg^{-1}. The highest fertilizer rate also increased soil K test levels in the 20- to 30-cm depth increment below the location of the band, but no difference was observed for the maintenance rate. The increase in soil K test levels at 20 to 30 cm for the highest K rate was likely the result of K leaching and may indicate that this rate was too high at the point of application to be retained by the soil. Rehm and Lamb (2004) also attributed higher K test levels in the soil below the fertilizer band to leaching. In contrast to P, soil surface K test levels declined, or at least showed a declining trend, for the broadcast treatments at BR for the maintenance rate treatment (Fig. 2B) and no buildup of soil K test levels occurred for the highest K fertilizer rate (Fig. 2C). These results were surprising since the biennial maintenance fertilizer rate was nearly equivalent to the actual annual K removal rates in seed of 40 kg K ha^{-1}, and the highest fertilizer rate exceeded the amount of K removed in seed. On the other hand, the 0- to 10-cm soil layer at the IR position of broadcast treatments showed an increase in soil K test levels for NTBC and an increasing trend for STBC at the maintenance rate (Fig. 2B) and an increase of 60 mg K kg^{-1} for NTBC and 73 mg K kg^{-1} for STBC at the highest K fertilizer rate (Fig. 2C). Higher soil K test levels at IR than BR positions agree with findings from others (Tyler and Howard, 1991; Howard et al., 1999; Varsa and Ebelhar, 2000). Mallarino and Borges (2006) also found that no-till systems at the 0- to 5-cm depth increment at IR had higher soil K test levels when K was broadcast-applied but they found no differences in chisel-disk or when no K was applied. We speculate that greater K test levels in the soil surface at IR than BR positions for the broadcast treatments in our study is the result of K leaching out of mature plants before harvest. Oltmans et al. (2011) showed that substantial K leaching occurs in standing corn and soybean plants between physiological maturity and harvest. This leaching would not occur for P since this nutrient becomes part of the plant tissues and P is released to the soil after tissues are decomposed. Another possible explanation as to why soil K test levels increased at the IR position of broadcast treatments is by mixing of soil and fertilizer during strip-till operation or by coulters during planting. However, this is not likely since it would be expected to influence soil P test levels as well, and we did not observe such effect for P (Fig. 1B and 1C).

It is obvious from our study that the use of RTK satellite navigation technology, which allows for maintenance of crop rows and band applications of immobile nutrients always in the same location, can intensify the formation of patterns of varying fertility levels in the field. These patterns can have important implications for soil sampling. It is clear that within treatment the three BR sampling positions were similar to each other but differed substantially relative to the IR position for soil P and K test levels (Table 1 and Fig. 1 and 2). The effect of fertilizer placement and rate on soil P and K test levels for the strip-till treatments (STBC and STDB) was calculated using different ratios of IR to BR sampling (Table 2). Those levels were compared to a true mean, defined as the value calculated from the average of test values from one sample collected at IR and three samples collected at BR (1:3 ratio of IR/BR cores) for the NTBC treatment. These calculations were made based on the top 20 cm of soil to include the subsurface fertilizer band. As indicated by Mallarino and Borges (2006) a shallow sample that does not include the subsurface fertilizer band can result in inaccurate soil fertility estimates.

For STBC soil P test levels were not different than the true mean regardless of the sampling ratio used or the fertilizer rate (Table 2). This indicates that for soil P measurements when fertilizer is broadcast, the sampling strategy in strip-till can be the same as for no-till broadcast systems, and samples could be collected with no regard to the location of the crop row. On the other hand, always sampling in the location of the tilled strip (IR position) overestimated soil K test levels. Averaged across all fertilizer rates, the 1:0 sampling ratio overestimated soil K test levels by 28 mg K kg^{-1} relative to the true mean. However, for soil K test levels the comparison to the true mean needs to be considered with caution because K accumulation occurred at IR for the NTBC treatment as well (Fig. 2C). As previously discussed, K accumulation at IR for broadcast treatments is likely caused by K leaching out of standing plants during senescence (Oltmans et al., 2011). The fact that K accumulation occurs at IR when successive planting is done in the location of the previous crop row indicates that for broadcast applications in no-till and strip-till, sampling position with respect to the crop row is an important consideration when determining K fertility. For instance the 42, 62, and 83 Kg K ha^{-1} rates had true mean levels recommending fertilization to increase soil K test levels to at least the critical level of 150 mg K kg^{-1} needed to maximize corn and soybean production (Fernández and Hoeft, 2009). Those same K rates in the strip-till treatments showed no need to apply additional fertilizer to increase soil K test levels when using a 1:0 sampling ratio. Although not statistically different than the true mean, increasing the ratio of IR/BR samples to 1:1 resulted in numerically greater soil K test levels, and collecting samples that do not account for the higher soil K test levels

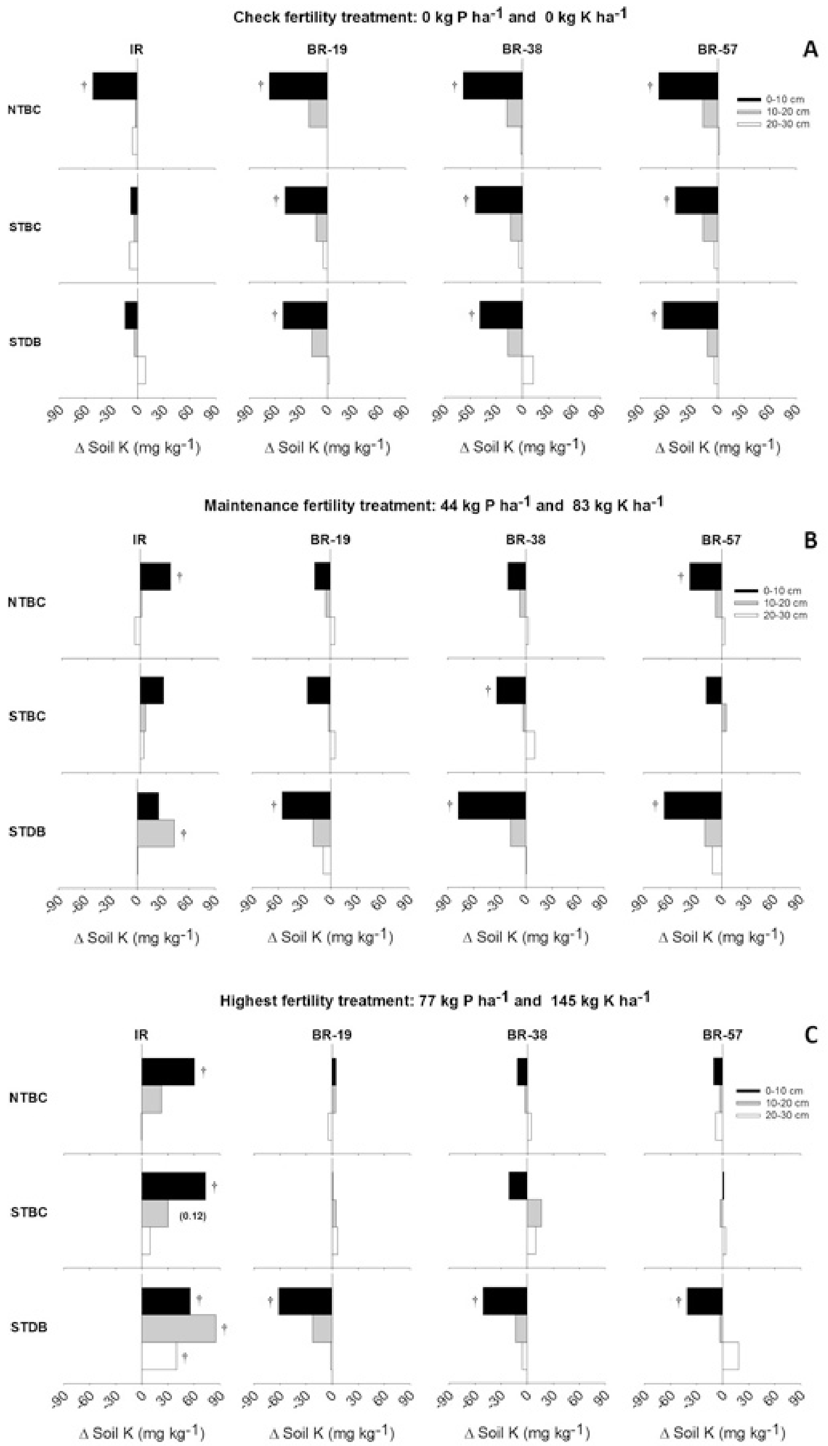

Fig. 2. Change in mean soil K test level from pre-treatment levels in 2007 to fall 2010 at various soil depth increments for different positions with respect to the crop row [in the crop row (IR) and between the crop rows (BR) 19, 38, and 57 cm from the IR] for no-till/broadcast (NTBC), strip-till/broadcast (STBC), and strip-till/deep-band (STDB) tillage/fertilizer placement treatments and three fertilizer rates (graphs A, B, C). † Indicate significant differences at *P* < 0.1; actual probability indicated between parenthesis for 0.15 ≥ *P* ≥ 0.1.

Table 2. Calculated mean soil P and K test level in fall 2010 for the top 20 cm of soil for different P and K fertilizer rates with various ratios of samples collected in the crop row (IR) to between the crop rows (BR) for strip-till broadcast (STBC) and strip-till deep-band (STDB) compared to the true mean calculated for no-till broadcast (NTBC).

P–K rate	NTBC True mean	STBC					STDB				
	1:3	1:3	1:2	1:1	1:0	0:3	1:3	1:2	1:1	1:0	0:3
kg ha^{-1}	mg P kg^{-1}										
0–0	12	17	17	16	15	18	12	12	11	10	13
22–42	21	19	19	19	18	20	15	16	19	26	11**
33–62	20	21	20	19	16	23	19	21	25	35†	14*
44–83	16	22	21	20	18	23	25*	29**	37**	62**	12
55–104	26	24	24	23	21	25	25	29	38*	64**	12**
66–125	24	30	29	28	24	32	26	30	39**	66**	13**
77–145	26	33	33	32	30	34	23	26	34	56**	12**
	mg K kg^{-1}										
0–0	128	125	127	131	143	119	120	121	125	134	115†
22–42	139	132	136	143	164†	122	131	135	144	170*	118**
33–62	143	148	152	161†	187**	135	138	143	153	183**	123*
44–83	135	136	138	143	157†	128	148†	155**	167**	206**	129
55–104	151	147	150	157	176*	137	146	153	168*	211**	124**
66–125	157	150	154	163	187*	138	162	171†	191**	249**	132**
77–145	155	161	165	172	193**	149	153	161	179**	230**	127**

* Significant differences at $P < 0.05$.

** Significant differences at $P < 0.01$.

† Significant differences at $P < 0.1$.

at IR (0:3 ratio) resulted in numerically smaller soil K test levels. Our data indicate that the 1:3 or 1:2 sampling ratio would be most appropriate to measure soil K test levels in fields where the planting band remains constant from year to year.

For STDB using a 1:3 or 1:2 sampling ratio was adequate regardless of the fertilizer rate (Table 2). The 44–84 kg P–K ha^{-1} rate showed an increase for these sampling ratios, but it was likely the result of a lower-than-expected soil test level for the true mean, for which there is no apparent explanation. We also observed that for low P–K rates (22–42 and 33–62 kg P–K ha^{-1}) it may be possible to soil sample at an IR/BR ratio of 1:1 without overestimating soil P or K test levels relative to the true mean. This would indicate that in fields with adequate fertility where P and K fertilizers are applied only in small quantities or as a starter application, the fertilizer band should not pose a substantial challenge for accurate soil sampling. On the other hand, for maintenance P and K fertilizer rates (44–83 kg P–K ha^{-1} or greater) the IR/BR ratio of 1:1 or 1:0 will cause overestimation of soil P and K test levels relative to the true mean. For instance, the true mean soil P and K test levels of the higher P and K fertilizer rate treatments would indicate the need to apply a fertilizer rate equal to what the crop removes to maintain fertility levels. However, soil test results from the 1:0 sampling ratio were above 33 mg P kg^{-1} and 200 mg K kg^{-1} where additional fertilization is not recommended because there is no expectation of a yield response to additional fertilizer (Fernández and Hoeft, 2009). Similarly, avoiding sampling at the IR is not recommended since it would cause substantial underestimation of the true fertility. This is because banding all the P and K fertilizer, as shown in Fig. 1B and 1C and Fig. 2B and 2C, respectively, caused a depletion of soil P and K test levels at BR similar to when no P or K fertilizers were applied (Fig. 1A and Fig. 2A, respectively). Our results are in contrast to those of Rehm et al. (1995) who indicated it is best to avoid sampling the fertilizer band. Our results indicate that avoiding the fertilizer band would result in overapplication of fertilizer. While this overapplication is highly unlikely to result in a negative impact on seed yield, it can result in lower short-term financial return on the fertilizer investment.

Starting soil P test levels in fall 2007 were 22 mg P ha^{-1} for NTBC and STBC and 21 mg P ha^{-1} for STDB. Examining soil test levels in fall 2010 using the 1:3 ratio for each of the tillage/fertilizer placement treatments showed maintenance or a slight buildup with the 44 kg P ha^{-1} rate, except for the NTBC that started at the 55 kg P ha^{-1} rate (Table 2). Though as mentioned earlier, we suspect that the soil test level for the 44 kg P ha^{-1} rate for NTBC was lower than expected, thus this fertilizer rate was likely sufficient to maintain or slightly buildup soil P test levels and agrees with measured P removal in seed. On the other hand, starting soil K test levels were 160, 150, and 158 mg K ha^{-1} for NTBC, STBC, and STDB, respectively. Except for STBC where the highest K rate (145 kg K ha^{-1}) increased soil K test levels, rates considered sufficient to maintain or buildup soil K test levels by current recommendations (Fernández and Hoeft, 2009) and based on actual removal rates for this study failed to do so (Table 2). In a recent survey of soil fertility status of soil in Illinois, Fernández et al. (2012) showed that 46% of the sampled fields were below the critical level for K. Also, of the total number of fields sampled approximately 32% had adequate P fertility (above the critical level) at the same time that K fertility was below the critical level. These results along with our results, though limited to few fields and soils, may reflect either a need to evaluate current K recommendations for Illinois or that the soils in our study fail to build up with the fertilizer rates used. Finally the 1:3 sampling ratio showed no difference in soil P and K test levels for different tillage/fertilizer placement treatments and indicate that fertilizer rate should not be adjusted based on tillage or fertilizer application method. Of course this is purely from a soil test measurement standpoint. Whether or not adjustments should be made to ensure adequate nutrient availability to the crop when fertilizers become highly concentrated in a small fraction of the soil is a question that remains to be answered and one that was beyond the scope of our study.

CONCLUSIONS

Soil P and K test levels were highly related to the placement method but not to tillage since both NTBC and STBC showed similar results. Within treatment the different sampling positions for BR were always similar to each other. Deep banding the fertilizer reduced the surface to subsurface P and K stratification ratio by increasing test levels in the subsurface with the fertilizer application, and by decreasing soil test levels in the surface as crops likely continued to remove nutrients from that layer. Deep banding the fertilizer created a pattern of high soil P and K test levels at IR and lower levels at BR. Movement of P and K below the fertilizer band occurred with the highest fertilizer rate. Also, maintaining the crop row always in the same position increased soil K test levels, but no soil P test levels, at the 0- to 10-cm depth increment at IR compared to BR positions in all tillage/fertilizer placement treatments. This increase in soil K test levels at IR was likely the result of greater K leaching from plant materials before harvest compared to P. Changes in soil P test levels averaged across sampling position with respect to the crop row followed closely what was expected in terms of incline, decline, or maintenance of soil P levels by current recommendations and as measured by actual P removal rates in seed. Conversely, soil K test levels were not maintained or increased as expected by current recommendations or measured K removal rates in seed, possibly indicating a need to re-evaluate the current recommendation system at least for the soils in the study. Nonetheless, the fact that changes in soil P and K test levels were similar across the different treatments indicated that fertilizer rate need not be adjusted based on the tillage/fertilizer placement conditions of this study.

This study was done for a corn–soybean rotation, so we can only speculate the results may be applicable to other crop rotations as well. In general this study clearly showed that when the fertilizer band and the planting row are maintained in the same location from year to year, sampling location is an important consideration. Underestimation of soil test levels can occur if the band is deeper than the recommended sampling depth or the location of the band (for P and K) or the planting row (for K) is avoided during sampling. On the contrary, if soil samples are collected only from the location of the fertilizer band, this would result in overestimation of soil P and K test levels. This study showed that this can be a substantial mistake when the overestimation of soil fertility indicates no need for fertilizer application when actual soil test levels may be yield limiting. In systems where RTK satellite navigation technology is used and the location of the fertilizer band or planting row is maintained constant, a ratio of 1:3 IR/BR sampling procedure appears to be adequate to estimate soil fertility across a wide range of P and K fertilizer rates and soil test levels. While this approach appears to be adequate for both P and K, the fact that K accumulation occurred at IR in the NTBC treatment may not allow an accurate representation for soil K test.

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REFERENCES

Bordoli, J.M., and A.P. Mallarino. 1998. Deep and shallow banding of phosphorus and potassium as alternatives to broadcast fertilization for no-till corn. Agron. J. 90:27–33. doi:10.2134/agronj1998.00021962009000010006x

Borges, R., and A.P. Mallarino. 2000. Grain yield, early growth, and nutrient uptake of no-till soybean as affected by phosphorus and potassium placement. Agron. J. 92:380–388.

Borges, R., and A.P. Mallarino. 2001. Deep banding phosphorus and potassium fertilizers for corn production under ridge tillage. Soil Sci. Soc. Am. J. 65:376–384. doi:10.2136/sssaj2001.652376x

Borges, R., and A.P. Mallarino. 2003. Broadcast and deep band placement of phosphorus and potassium for soybean managed with ridge tillage. Soil Sci. Soc. Am. J. 67:1920–1927. doi:10.2136/sssaj2003.1920

Duiker, S.W., and D.B. Beegle. 2006. Soil fertility distributions in long-term no-till, chisel/disk and moldboard plow/disk systems. Soil Tillage Res. 88:30–41. doi:10.1016/j.still.2005.04.004

Ebelhar, S.A., and E.C. Varsa. 2000. Tillage and potassium placement effects on potassium utilization by corn and soybean. Commun. Soil Sci. Plant Anal. 31:2367–2377. doi:10.1080/00103620009370591

Farmaha, B.S., F.G. Fernández, and E.D. Nafziger. 2011. No-till and strip-till soybean production with surface and subsurface phosphorus and potassium fertilization. Agron. J. 103:1862–1869. doi:10.2134/agronj2011.0149

Farmaha, B.S., F.G. Fernández, and E.D. Nafziger. 2012. Distribution of soybean roots, soil-water, phosphorus and potassium concentrations with broadcast and subsurface-band fertilization. Soil Sci. Soc. Am. J. 76:doi:20.2136/sssaj2011.0202.

Fernández, F.G., S.M. Brouder, C.A. Beyrouty, J.J. Volenec, and R. Hoyum. 2008. Assessment of plant available potassium for no-till, rainfed soybean. Soil Sci. Soc. Am. J. 72:1085–1095. doi:10.2136/sssaj2007.0345

Fernández, F.G., S.M. Brouder, J.J. Volenec, C.A. Beyrouty, and R. Hoyum. 2009. Root and shoot growth, seed composition, and yield components of no-till rainfed soybean under variable potassium. Plant Soil 322:125–138. doi:10.1007/s11104-009-9900-9

Fernández, F.G., B.S. Farmaha, and E.D. Nafziger. 2012. Soil fertility status of soils in Illinois. Commun. Soil Sci. Plant Anal. (in press).

Fernández, F.G., and R.G. Hoeft. 2009. Managing soil pH and crop nutrients. In: E.D. Nafziger, editor, Illinois agronomy handbook. 24th ed. Univ. of Illinois, Urbana. p. 91–112.

Frank, K., D. Beegle, and J. Denning. 1998. Phosphorus. In: J.L. Brown, editor, Recommended chemical soil test procedures for the North Central region. North Central Regional Publ. no. 221. (Rev.). Missouri Exp. Stn. Publ. SB 1001. Univ. of Missouri, Columbia. http://extension.missouri.edu/explorepdf/specialb/sb1001.pdf (accessed 7 Oct. 2011). p. 21–29.

Hairston, J.E., W.F. Jones, P.K. McConnaughey, L.K. Marshall, and L.B. Gill. 1990. Tillage and fertilizer effects on soybean growth and yield on three Mississippi soils. J. Prod. Agric. 3:317–323.

Holanda, F.S.R., D.B. Mengel, M.B. Paula, J.G. Carvalho, and J.C. Bertoni.

1998. Influence of crop rotations and tillage systems on phosphorus and potassium stratification and root distribution in soil profile. Commun. Soil Sci. Plant Anal. 29:2383–2394. doi:10.1080/00103629809370118

Hooker, M.L. 1976. Soil sampling intensities required to estimate available N and P in five Nebraska soil types. MS thesis. Univ. of Nebraska, Lincoln.

Howard, D.D., M.E. Essington, and D.D. Tyler. 1999. Vertical phosphorus and potassium stratification in no-till cotton soils. Agron. J. 91:266–269. doi:10.2134/agronj1999.00021962009100020014x

Hudak, C., R. Stehouver, and J. Johnson. 1989. An evaluation of K rate, placement, and tillage systems for soybeans. J. Fert. Issues 6:25–31.

Kitchen, N.R., J.L. Havlin, and D.G. Westfall. 1990. Soil sampling under no-till banded phosphorus. Soil Sci. Soc. Am. J. 54:1661–1665. doi:10.2136/sssaj1990.03615995005400060026x

Mackay, A.D., E.J. Kladivko, S.A. Barber, and D.R. Griffith. 1987. Phosphorus and potassium uptake by corn in conservation tillage systems. Soil Sci. Soc. Am. J. 51:970–974. doi:10.2136/sssaj1987.03615995005100040027x

Mallarino, A.P., and R. Borges. 2006. Phosphorus and potassium distribution in soil following long-term deep-band fertilization in different tillage systems. Soil Sci. Soc. Am. J. 70:702–707. doi:10.2136/sssaj2005.0129

Miner, G., and E. Kamprath. 1971. Reactions and availability of banded polyphosphate in field studies. Soil Sci. Soc. Am. Proc. 35:927–930. doi:10.2136/sssaj1971.03615995003500060024x

Morrison, J.E. 2002. Strip tillage for "no-till" row crop production. Appl. Eng. Agric. 18:277–284.

Oltmans, R.R., A.P. Mallarino, and C.X. Villavicencio. 2011. Potassium uptake, removal, and recycling with residue in corn and soybean. In: Annual Meetings Abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Peck, T.R., and P.N. Soltanpour. 1990. The principles of soil testing. In: R.L. Westerman, editor, Soil testing and plant analysis. SSSA Book Ser. 3. SSSA, Madison, WI. p. 1–9.

Petersen, R.G., and L.D. Calvin. 1996. Sampling. p. 1–17. In: D.L. Sparks, editor, Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.

Randall, G.W., and J. Vetsch. 2008. Optimum placement of phosphorus for corn/soybean rotations in a strip-tillage system. J. Soil Water Conserv. 63:152A–153A. doi:10.2489/jswc.63.5.152A

Rehm, G.W., and J.A. Lamb. 2004. Impact of banded potassium on crop yield and soil potassium in ridge-till planting. Soil Sci. Soc. Am. J. 68:629–636. doi:10.2136/sssaj2004.0629

Rehm, G.W., G.W. Randall, A.J. Scobbie, and J.A. Vetsch. 1995. Impact of fertilizer placement and tillage system on phosphorus distribution in soil. Soil Sci. Soc. Am. J. 59:1661–1665. doi:10.2136/sssaj1995.03615995005900060022x

SAS Institute. 2009. The SAS system for windows. v.9.2. SAS Inst., Cary, NC.

Shapiro, C.A. 1988. Soil sampling fields with a history of fertilizer bands. Soil Sci. News. Nebraska Coop. Ext. Serv. Vol. 10, No. 5.

Sharpley, A.N., and A.D. Halvorson. 1994. The management of soil phosphorus availability and its impact on surface water quality. In: R. Lal and B. A. Stewart, editors, Soil processes and water quality. Advances in soil science. Lewis Publ., Boca Raton, FL. p. 7–90.

Shear, G.M., and W.W. Moschler. 1969. Continuous corn by the no-tillage and conventional tillage method: A six-year comparison. Agron. J. 61:524–526. doi:10.2134/agronj1969.00021962006100040012x

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. doi:10.2134/jeq1998.00472425002700020006x

Tyler, D.D., and D.D. Howard. 1991. Soil sampling patterns for assessing no-tillage fertilization techniques. J. Fert. Issues 8:52–56.

Varsa, E.C., and S.A. Ebelhar. 2000. Effect of potassium rate and placement on soil test variability across tillage systems. Commun. Soil Sci. Plant Anal. 31:2155–2161. doi:10.1080/00103620009370572

Vetsch, J.A., and G.W. Randall. 2002. Corn production as affected by tillage system and starter fertilizer. Agron. J. 94:532–540. doi:10.2134/agronj2002.0532

Vitosh, M.L., J.W. Johnson, and D.B. Mengel. 1996. Tri-state fertilizer recommendations for corn, soybeans, wheat and alfalfa. Ext. Bull. E-2567. Michigan State Univ. Coop. Ext. Serv., Lansing.

Warncke, D., and J.R. Brown. 1998. Potassium and other cations. In: J.L. Brown, editor, Recommended chemical soil test procedures for the North Central region. North Central Regional Publ. No. 221. (Rev.). Missouri Exp. Stn. Publ. SB 1001. Univ. of Missouri, Columbia. http://extension.missouri.edu/explorepdf/specialb/sb1001.pdf (accessed 7 Oct. 2011). p. 31–33.

Yin, X., and T.J. Vyn. 2002a. Residual effect of potassium placement and tillage systems for corn on subsequent no-till soybean. Agron. J. 94:1112–1119. doi:10.2134/agronj2002.1112

Yin, X., and T.J. Vyn. 2002b. Soybean response to potassium placement and tillage alternatives following no-till. Agron. J. 94:1367–1374. doi:10.2134/agronj2002.1367