STRIP-TILL AND NO-TILL SOYBEAN GROWTH AND DISTRIBUTION OF ROOTS AND SOIL PHOSPHORUS, POTASSIUM, AND WATER WITH BROADCAST AND SUBSURFACE-BAND FERTILIZATION

BY

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DISSEPTION

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ABSTRACT

Method of application of the slowly-mobile nutrients phosphorus (P) and potassium (K) in conservation tillage systems were little mixing of the soil occurs, is an important management decision as placement can influence the availability to these nutrients to the crop. The objectives of this study were to determine the effect of no-till, strip-till, and P and K rate and placement on soybean [Glycine max (L.) Merr.] root distribution, shoot growth and nutrient accumulation, seed yield and seed composition; and to quantify treatment effects on the distribution of P, K, and water in the soil. A three-year field experiment was conducted in Champaign, Illinois on Flanagan silt loam and Drummer silty clay loam soils with tillage and fertilizer placement as the main (whole) plot: no-till broadcast (NTBC), no-till deep band (NTDB), and strip-till deep band (STDB) with deep banding at 15 cm. The split-plot consisted of four P application rates (0, 12, 24, 36 kg P ha\(^{-1}\) yr\(^{-1}\)) and the split-split plot consisted of four K application rates (0, 42, 84, 168 kg K ha\(^{-1}\) yr\(^{-1}\)). Vegetative samples were taken throughout the growing season to measure various growth components. Roots and soil P, K, and water were measured periodically during the season at in-row (IR) and between-rows (BR) positions. Seed yield and yield components were measured at harvest and seed was analyzed for oil, protein, P and K concentration. Seed yield for STDB was 3.06 Mg ha\(^{-1}\) and 10 % greater than NTBC and 7 % greater than NTDB. At the same time, NTDB produced a small but significant 0.1 Mg ha\(^{-1}\) (4%) greater yield than NTBC. Initial soil P levels were marginal for soybean production and P fertilization in the no-till systems increased yields. However, STDB produced consistently higher yields than the no-till systems and showed no response to P fertilization. Soils had adequate starting K fertility and additional K produced no yield increase. Deep banding increased P and K test level beneath the row and lowered soil surface test-values.
compared to broadcast applications. Since seed yield is not reduced and subsurface banding of fertilizer reduces fertility levels on the soil surface, this placement method may be a viable option for soybean production in fields where high potential for surface P runoff presents an environmental concern. There was no root proliferation in response to the concentrated band of fertilizer. Regardless of treatment, soybean root densities were greatest within the top 10 cm of the soil. Throughout the growing season there was greater water availability in the top 10 cm of the soil at the BR position in STDB than in the no-till systems (NTBC and NTDB). This was likely the result of a combination of greater water infiltration with strip-till and the crop residue present in the BR position that diminished the potential for the infiltrated water to evaporate. The top 10 cm of the soil at the BR position also had the greatest change in soil P for all tillage/placement systems, likely as result of crop uptake. Within the top 10 cm of the soil at the BR position STDB also had smaller root density than NTBC at the R3 development stage. Greater nutrient accumulation with a smaller root system in STDB relative to NTBC indicate that overall STDB provided improved conditions for nutrient uptake, possibly as a result of greater water availability. Above-ground dry biomass was consistently higher for STDP than NTBC especially during the late vegetative/early reproductive stage to about R4 development stage. Similarly, STDP produced greater plant height, leaf area index (LAI), and crop growth rate (CGR) compared to NTBC. These findings indicate that STDP is advantageous compared to the no-till systems for soybean production.
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CHAPTER 1

INTRODUCTION AND OBJECTIVES

Second to corn (Zea mays L.), soybean [Glycine max (L.) Merr.] is the most widely grown crop in Illinois representing 12% of the total soybean hectares planted in the U.S. in 2010 (USDA/NASS 2010). Over the years, there has been increasing interest among Illinois farmers to manage soybeans with no-till (NT). As an example, the percentage of farms using NT increased from 45.6 in 2004 to 51 in 2006 (IDOA, 2006). The advantages of using NT over conventional tillage systems include improved soil conservation (Edwards, 1988; Rhoton, 2000) greater yields in dry years, and savings in operational cost (Smart, 1999). Another advantage of NT over conventional tillage is that large amounts of crop residue left on the soil surface with NT can increase organic matter content of the soil surface (Tyler and Overton, 1982; Balesdent et al., 2000). However, the high-residue content left on the soil surface can be a challenge for soybean production when soybean is grown in rotation with corn. Soils covered with crop residue have higher albedo and can delay evaporation of water from the wet fields preventing early planting or delaying germination and growth due to cooler soil conditions (Doran et al., 1984; Jones, 1994). Historically, since corn is planted before soybean, these conditions have been a greater concern for corn than for soybean production. However, in recent years, studies with early soybean planting have shown seed yield advantages compared to May or June planting (Lueschen, et al., 1992; Grau et al., 1994; De Bruin and Pedersen, 2008). These findings may encourage farmers to start planting soybeans earlier in the season and possibly create similar challenges to those observed for early-planted corn. Therefore, it
would be beneficial to use management practices that can allow soil to warm and dry quickly for early soybean planting.

Compared to no-till, strip-till (ST) can allow the soil to warm up and dry faster as the tillage operation removes crop residue from the soil surface and increases soil aeration (Perez-Bidegain et al., 2007). Because of the possibility to create warmer and drier conditions, strip-till may provide a viable alternative for early soybean planting (Opoku et al., 1997; Licht and Al-Kaisi, 2005).

Strip-tillage is another method of conservation tillage in which the planting row is tilled 15-20 cm deep, 3-5 cm wide at the bottom, and 20-25 cm wide at the soil surface, with a residue-free berm approximately 5 to 8 cm tall and much of the residue left between the planting rows. Strip-till provides soil and water conservation benefits similar to NT by leaving crop residue coverage on most of the soil surface (Jones et al., 1994; Morrison Jr., 2002). In addition, strip-till provides the ease of planting and improved seed germination and early plant growth benefits of conventional tillage by clearing crop residue away from the seedbed (Vyn and Raimbault, 1992). Strip-till has also been reported to improve soybean seed yield compared to NT (Vyn et al., 1998).

The wide adoption of NT for crop production where broadcast phosphorus (P) and potassium (K) fertilizer applications are routinely performed can lead to stratification of these nutrients with higher concentrations in the surface than the subsurface layers (Mullen and Howard, 1992). Furthermore, plant uptake of P and K from the sub-surface layers adds to the vertical heterogeneity of these nutrients (Mackay et al., 1987; Karlen et al., 1991; Robbins and Voss, 1991; Holanda et al., 1998; Vyn et al., 2002) and may render these nutrients less availability to the crop (Singh et al., 1966; Belcher and
Ragland, 1972; Moschler and Martens, 1975). Alternatively, deep band placement of P and K can be advantageous compared to broadcast surface application to increase subsurface test levels. Increased soybean seed yield in response to deep banding of fertilizers has been inconsistent. Some have reported yield advantages (Buah et al., 2000; Ebelhar and Varsa, 2000), while others have not (Hudak et al., 1989; Rehm and Lamb, 2004). These conflicting reports may indicate that there are other factors besides nutrient distribution in the soil that could impact nutrient availability and ultimately soybean seed yield.

Root growth plays an important role in crop production and its effect on yield could depend on availability of soil water and nutrients in the root zone (Peters and Runkles, 1967; Lynch, 1995). As mentioned earlier, broadcast P and K applications in NT can result in a nutrient-rich surface. Several studies have indicated potential drawbacks of having the majority of the fertility concentrated in the surface layer if such layer dries out during droughty periods (Eckert and Johnson, 1985; Ebelhar and Varsa, 2000). Therefore, supplying P and K fertilizer deeper in the soil where presumably there is greater water availability and possibly more root activity can increase nutrient availability and uptake for soybeans (Mengel et al., 1988; Borges and Mallarino, 2000; Yin and Vyn, 2002).

Changes in soil water and nutrient availability in relation to tillage or fertilizer placement treatments may account for some of the differences in plant growth and development and nutrient accumulation. Borges and Mallarino (2003) found that supplying P and K at 15 to 20 cm deep in ridge-till increased the uptake of both nutrients for soybean as early as the V5-V6 development stage compared to broadcast treatments.
Yin and Vyn (2003) observed that compared to surface broadcast, 10 cm deep placement of K increased plant K uptake, seed K concentration, and oil concentration of soybean in low-K testing soils. The effect of deep band placement on early plant growth and nutrient uptake compared to broadcast application has been more consistent for corn than for soybean (Mallarino et al., 1999).

While only few studies have been conducted to study the effect of strip-till coupled with deep band placement of P and K on soybean production, less is known about their effect on roots, distribution of water and P and K in the soil profile, and nutrient accumulation in soybean tissues. Hence, the first objective of this study was to measure the effect of rate and placement of P and K on soybean seed yield and composition, yield components, P and K removal, and growth components of soybean grown under no-till and strip-till systems. The second objective was to study the effect of tillage/fertilizer placement treatment and rate of P and K application on seasonal changes in roots, soil, and water distribution. An additional objective was to investigate the impact of the treatments on soil P and K test levels.

The results of this study have been divided into three chapters (chapter 2 through 4). Each chapter was organized as a standalone work and has been formatted to be published in scientific peer-reviewed journals. Chapter 2 discusses the effects of treatments on soybean seed yield, P and K concentrations and accumulation, yield components, trifoliate tissue nutrient analysis at R1 development stage, and soil P and K test levels measured at the start and the end of the experiment. Chapter 3 focuses on the effects of treatments on seasonal roots, soil water, P, and K concentrations, and plant P and K uptake rates. Chapter 4 presents the treatment effects on season-long soybean plant
growth and above-ground tissue nutrient accumulation, and seed protein and oil
concentrations and yield. The final chapter, Chapter 5, provides an interpretative
summary of findings and implications, as well as a discussion on limitations of this work
and future research opportunities.
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CHAPTER 2
NO-TILL AND STRIP-TILL SOYBEAN PRODUCTION WITH SURFACE AND SUB-SURFACE PHOSPHORUS AND POTASSIUM FERTILIZATION

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ABSTRACT

Compared to no-till, strip-till can offer improved seedbed conditions and deep banding of fertilizer. The objective of this study was to quantify the effect of rate and placement of phosphorus (P) and potassium (K) in no-till and strip-till systems on soybean [Glycine max (L.) Merr.] seed yield. A three-year field experiment was conducted near Urbana, Illinois on Flanagan silt loam and Drummer silty clay loam soils, with soybean planted following corn (Zea mays L.). Tillage/fertilizer placement was the main plot with no-till/broadcast (NTBC); no-till/deep band (NTDB); and strip-till/deep band (STDB); deep band placement was 15 cm beneath the planted row. Phosphorus–fertilizer rate (0, 12, 24, and 36 kg P ha\(^{-1}\) yr\(^{-1}\)) was the subplot, and K-fertilizer rate (0, 42, 84, and 168 kg K ha\(^{-1}\) yr\(^{-1}\)) was the sub-subplot. Soil water, soil and trifoliate P and K, and seed yield were measured. Overall, STDB produced 3.1 Mg seed ha\(^{-1}\), 10 and 7% more yield than NTBC and NTDB, respectively. Seed yield, number of pods plant\(^{-1}\), and trifoliate P concentration and accumulation increased with P fertilization uniformly across tillage/fertilizer placement indicating that fertilization cannot be reduced with deep band applications relative to broadcast applications without a reduction in seed yield, but deep banding increase sub-surface soil test levels. Potassium fertilization decreased seed yield in both no-till treatments but not in the STDB system. While P and K placement
produced no differences, improved soybean yield and nutrient accumulation resulted from a tillage effect with STDB relative to the no-till treatments.

Abbreviations: NTBC, no-till/broadcast; NTDB, no-till/deep band; STDB, strip-till/deep band.

INTRODUCTION

Soybean is an important crop in the United States, with 31.1 million hectares planted in 2010 (USDA/NASS, 2010). In 2008, 62% of full-season soybeans and 76% of double-cropped (planted after wheat harvest) soybeans in the U.S. were planted under no-tillage or some other conservation tillage system (CTIC, 2008). No-till is often preferred over conventional tillage because it can result in operational cost savings to farmers, reduce soil erosion (Trewavas, 2004), and conserve soil water (Williams et al., 2009).

No-till soybean production has challenges, however. Soybean typically follows corn in rotation, and the large amount of corn crop residue on the soil surface at planting can be a challenge for no-till soybean production. Soils covered with crop residue have higher albedo, which slows warming and evaporation of water in the soil surface, often resulting in delays in planting or germination, and slow early growth (Jones et al., 1994). Such delays can be detrimental to soybean yield (De Bruin and Pedersen, 2008).

The strip-till system is one in which a narrow (15 to 25 cm wide) band is tilled to a depth of 10 to 20 cm and the new crop row planted atop this strip. This system provides most of the soil and water conservation benefits of no-till, while improving seedbed condition similar to conventional tillage systems (Jones et al., 1994; Morrison, 2002). Improved seedbed conditions by removing crop residue from the planting row in strip-till relative to no-till has been shown to enhance seed germination, faster early plant growth,
and grain yield for corn in soils that tend to be cool and wet in the spring (Vyn and Raimbault, 1992; Morrison, 2002; Vetsch and Randall, 2002; Randall and Vetsch, 2008). Compared to corn production, relatively less work has been done to assess benefits of strip-till for soybean production (Vyn et al., 1998; Randall and Vetsch, 2008).

Another possible advantage to strip-till is the opportunity it provides for simultaneous deep banding of fertilizers materials. Deep banding of fertilizer, especially P, may be beneficial to reduce surface P concentrations and lower potential environmental concern related to water runoff from fields with high P levels at the soil surface (Duiker and Beegle, 2006; Randall and Vetsch, 2008). In addition, deep banding of fertilizers has been hypothesized as an alternative to increase nutrient availability and improve fertilizer use efficiency. In much of the U.S. corn-belt soybean production is rainfed. In nutrient-stratified systems where P and K concentrations are high in the soil surface, excessive drying of that layer during reproductive stages – when soybean accumulate about 75% of their total P and K (Hanway and Weber, 1971)— may limit nutrient uptake (Yin and Vyn, 2002). However, Fernández et al. (2008, 2009) showed greater apparent K uptake in the top 5 cm of a vertically stratified no-till soil when intermittent rainfall provided adequate moisture during the growing season. Similarly, inconsistent response to deep banding of fertilizers has been reported for soybean seed yield. Some have reported yield advantages with deep band compared to broadcast fertilizer (Ebelhar and Varsa, 2000), while others have reported no advantage (Borges and Mallarino, 2000; Yin and Vyn, 2002; Rehm and Lamb, 2004). The limited amount of information on soybean production in strip-till and the lack of agreement on the effect of nutrient placement on soybean yield warrant further investigation.
The objective of this study was to quantify the effect of rate and placement of P and K fertilizers in no-till and strip-till systems on soybean seed yield. An additional objective was to quantify yield components and leaf nutrient concentrations to help explain the effect of treatments on soybean seed yield and the short-term effect of nutrient placement on soil P and K test levels.

MATERIALS AND METHODS

Site Description

A field experiment was conducted from 2007 through 2009 at the Crop Sciences Research & Education Center near Urbana, Illinois on a Flanagan silt loam soil (Fine, smectitic, mesic Aquic Argiudolls) intermixed with small areas of Drummer silty clay loam soil (Fine-silty, mixed, superactive, mesic Typic Endoaquolls). Pre-treatment test values in the top 18 cm of soil were: cation exchange capacity, 17 cmolc kg⁻¹; organic matter, 3.7%; pH (1:1 soil/water ratio) 5.7; Bray P₁ (colorimetric analysis), 20 mg P kg⁻¹; and ammonium acetate extractable K, 167 mg kg⁻¹. The P and K values were at least at sufficiency levels to maximize soybean production in Illinois (Fernández and Hoeft, 2009).

Treatments

Soybeans followed corn in a two-year, corn-soybean rotation. The study was set up in a split-split-plot arrangement in a randomized complete-block design with three replications. Three tillage/fertilizer placement treatments: no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB) were assigned to the main plot. Four P application rates (0, 12, 24, and 36 kg P ha⁻¹ yr⁻¹) were applied as split-plot treatments, and four K application rates (0, 42, 84, and 168 kg K ha⁻¹ yr⁻¹) were assigned
to the split-split plot within P fertilizer rates. For the unfertilized plots (0 kg P ha\(^{-1}\) yr\(^{-1}\) and 0 kg K ha\(^{-1}\) yr\(^{-1}\)) each tillage/fertilizer placement treatment received the corresponding soil disturbance created by the application equipment. Plots consisted of 76-cm rows (6 m wide) by 23 m in length.

The soybean study described here alternated with an identical study on corn, with treatments in the same plots in each crop; each year except the first, soybean rows were placed 10 cm to the same side of the corn rows from the previous crop. Treatments were applied approximately one month prior to planting using blends of P (0-45-0) and K (0-0-60).

Broadcast treatments were applied by hand using a spin-spreader. Deep banding of fertilizer treatments were applied 15 cm beneath the soil surface, directly underneath the planting row, using a Gandy Orbit Air applicator (Model 6212C, Gandy, Owatonna, MN). The NTDB treatments were applied using 2-cm-wide, low-disturbance, NH\(_3\) thin profile knives (minimum tillage knife Model 003-0000018, Fertilizer Dealer Supply, Philo, IL). For the STDB treatment, application was made with a unit consisting of a wavy cutting coulter and row cleaners (residue managers) in front of modified NH\(_3\) knives (original mole knife – Model 003-0100411, Fertilizer Dealer Supply) with closing discs (berm shapers) behind the mole knife. During the fertilizer application process the NTDB system disturbed the soil in an area 15 cm deep and about 2 cm wide at the bottom and 4 cm wide at the soil surface, with negligible surface residue disturbance. The STDB system disturbed the soil in a band about 17 cm deep, 4 cm wide at the bottom, leaving on the soil surface a residue-free berm approximately 5 to 8 cm tall and 25 cm wide. There was no soil disturbance before planting in the NTBC treatment.
Soybeans were planted 5 cm deep at a seeding rate of 376,000 seeds ha\(^{-1}\) using a John Deere 7200 Max Emerge vacuum planter with Yetter trash movers and openers. Plots were kept weed-free using glyphosphate [isopropylamine salt of N-(phosphonomethyl) glycine]. The cultivar Hi-Soy2846 (maturity group 2.8) was planted on 25 May 2007 and 13 June 2008; and cultivar Pioneer 93M42 (maturity group 3.4) was planted on 24 June 2009.

**Measurements**

Tissue analysis of the top fully developed trifoliate leaves at R1 development stage (Fehr and Caviness, 1977) is routinely used to determine the status of nutrients in the plant and the need for additional fertilization (Small and Ohlrogge, 1973). The uppermost fully developed trifoliate leaves of 20 plants were collected at R1 development stage. 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., Philadelphia, PA), and chemically analyzed for nutrient content. Analyses were done by A & L Great Lakes Laboratories, Inc., Fort Wayne, IN following the official methods of analysis of AOAC International (Horwutz, 2000).

Soil water content for the top 10 cm of the soil was monitored continuously during the growing season in all tillage/fertilizer placement treatments receiving 36-168 kg P-K ha\(^{-1}\) yr\(^{-1}\) rate using ECH\(_2\)O EC-5 moisture probes and Em-50 digital data loggers (Decagon Devices Inc., Pullman, WA).

Soil samples were collected from all the tillage/fertilizer placement treatments from the following fertilizer treatments 0-0, 36-0, 0-168, and 36-168 kg P-K ha\(^{-1}\) yr\(^{-1}\) that represent the combination of lowest and highest fertilizer applications. A three-composite
core soil sample was collected prior to treatment application and again at the end of the experiment, three years later, using a hand-held, 2-cm diameter probe. In the latter sampling the effect of localized P and K placement from the fertilizer band was captured by collecting three-composite core soil samples at the location of the band and three-composite core soil samples between bands. Cores were divided into the following depth increments: 0 to 5, 5 to 10, 10 to 18, and 18 to 50 cm. Soil samples were air dried, ground to pass through a 2 mm diameter sieve, and analyzed for P with the Bray P$_1$ extract and colorimetric analysis (Bray and Kurtz, 1945) and for K with the 1 M NH$_4$OAc extract (Warncke and Brown, 1998).

Samples for yield components were collected at maturity from an area of 66 cm by 76 cm (0.5 m$^2$) in P-K treatments receiving all possible combinations of 0 and 36 kg P ha$^{-1}$ yr$^{-1}$ and 0 and 168 kg K ha$^{-1}$ yr$^{-1}$. Yield components measured included plants m$^{-2}$, number of pods plant$^{-1}$, seeds pod$^{-1}$, and weight seed$^{-1}$ determined from 100 seeds corrected to 130 g kg$^{-1}$ moisture.

Machine harvest was done from the two center rows of each plot on 12 October 2007, 28 October 2008, and 12 November 2009. Yields were corrected to 130 g kg$^{-1}$ moisture. Seed samples were analyzed for P and K concentrations following the official methods of analysis of AOAC International (Horwutz, 2000).

**Statistical Analysis**

Soybean data were analyzed with the MIXED procedure of SAS (SAS Institute, 2009), with years, blocks and their interactions with treatments as random effects. Residuals for all analyses of variance were evaluated for normality based on the Shapiro-Wilk test in the UNIVARIATE procedure of SAS (SAS Institute, 2009) and homogeneity
of variances was examined visually from the residual plots (plot the residuals versus fitted values). Means comparison tests were made following the Tukey’s studentized range honestly significant difference (HSD) test to control experiment-wise error and the Tukey-Kramer test for unbalanced data. Analysis by orthogonal estimate statements was conducted for each of the tillage/fertilizer placement treatments with the unfertilized plots (0 kg P ha\(^{-1}\) yr\(^{-1}\) and 0 kg K ha\(^{-1}\) yr\(^{-1}\)) to more clearly determine the effect of tillage independent of the fertilizer placement effect. Treatment effects were declared significant at an alpha level of 0.1.

RESULTS AND DISCUSSION

All three years were characterized by large deviations from the normal 30-year mean (1980-2009) for precipitation and temperatures through the growing season (Table 2.1). The 2007 season was warmer and drier than average, while 2008 and 2009 were relatively cooler and wetter than average. Compared to the 30-yr mean, the period May-October in 2007 had 166 mm less precipitation and 6 fewer rain events, while 2008 had 207 mm greater precipitation with 8 more rain events, and 2009 had 191 mm greater precipitation and 20 more rain events. Relative to the 30-yr mean for the period May-October mean air temperature was 1.85\(^\circ\)C above in 2007, -0.37\(^\circ\)C in 2008, and -0.83\(^\circ\)C in 2009.

Soybean seed yield was significantly affected by tillage/fertilizer placement, P and K fertilizer rates, and the interaction of tillage/fertilizer placement with K fertilizer rate (Table 2.2). These treatment differences were observed for all three years, even in 2009 where a combination of late planting and cooler conditions (that made it necessary to change the cultivar and maturity group) likely resulted in 2.6 Mg ha\(^{-1}\) yield, which was
lower than 3.1 Mg ha$^{-1}$ in 2007 and 3.0 Mg ha$^{-1}$ in 2008. Averaged across years and P and K fertilizer rates, STDB produced a yield of 3.06 Mg ha$^{-1}$ (Table 2.3). This yield was 0.3 Mg ha$^{-1}$ (10%) greater than NTBC and 0.2 Mg ha$^{-1}$ (7%) greater than NTDB. At the same time, NTDB produced a small but significant 0.1 Mg ha$^{-1}$ (4%) greater yield than NTBC. Analysis by orthogonal estimate statements for the unfertilized plots (0 kg P ha$^{-1}$ yr$^{-1}$ and 0 kg K ha$^{-1}$ yr$^{-1}$) indicated that the yield difference was largely the result of tillage effect and not of fertilizer placement (Table 2.4). Several studies have indicated an advantage for crop production with strip-till because of improved crop growth in cool and wet soil conditions early in the growing season relative to no-till (Vyn and Raimbault, 1992; Vetsch and Randall, 2002). Even though seeding was not done early, our data clearly indicate an advantage for soybean production with strip-till and suggest that the advantage produced by strip-till may not be limited to only early-planted soybeans.

Averaged across all the growing seasons, volumetric soil water content ($\Theta_v$) within the top 10 cm of the soil for STDB was 0.24 cm$^3$ cm$^{-3}$, 4% greater than for the no-till treatments. This small but statistically significant difference indicates that greater water content in STDB may be providing an advantage for soybean production relative to the no-till treatments. Other studies have shown improved soil conditions with strip-till relative to no-till leading to better aggregate stability that can be important for water infiltration (Vyn and Raimbault, 1992; Vyn et al., 1998). Further, tillage has been shown to increase not only water infiltration but storage capacity of that water in the soil compared to no-till soils (Lipiec et al., 2006). Our results indicating that soybean yield was not responsive to fertilizer placement agree with other studies that showed no advantage to deep banding of fertilizer relative to broadcast applications (Yin and Vyn,
2002; Rehm and Lamb, 2004) and contrasts the study by Ebelhar and Varsa (2000) where deep banding enhanced soybean seed yield.

There was a positive linear response of soybean yield to P fertilizer rate (Figure 2.1). The tillage/fertilizer placement by P fertilizer rate interaction was not significant indicating similar yield response to P fertilizer rate across the three tillage/fertilizer placement treatments. This lack of difference further indicates no possibility to reduce P fertilizer rate with deep banding relative to broadcast applications without a reduction in seed yield. These results agree with those of Borges and Mallarino (2000) for no-till soybean production under broadcast and sub-surface band P applications. Soil concentrations at the start of the experiment were at the critical level recommended to maximize soybean production (Fernández and Hoeft, 2009). By fall 2009 soil test levels were below the critical level at 14 mg P kg$^{-1}$ for the 0 kg P ha$^{-1}$ rate and 19 mg P kg$^{-1}$ for the 12 kg P ha$^{-1}$ rate while the 24 and 36 kg P ha$^{-1}$ rates had increased P test levels above the critical level. The observed yield response is in agreement with current soil test P-based recommendations for Illinois and agrees with other U.S. corn-belt studies that showed soybean response in low P testing soils (less than 20 mg P kg$^{-1}$ by the Bray-P$_1$ extractant) (Rehm, 1986; Mallarino et al., 1991; Randall et al., 1997).

We observed no yield increase with increasing K fertilizer rate for the different tillage/fertilizer placement treatments (Figure 2.2). This supports the current university recommendations since initial soil test levels were above the recommended critical level to maximize yield (Fernández and Hoeft, 2009). It was surprising, however, that soybean yield decreased linearly as K fertilizer rate increased in the no-till treatments (NTBC and NTDB), but there was no response to K in the STDB treatment that yielded consistently
higher at all K fertilizer rates relative to the no-till treatments (Figure 2.2). Ebelhar and Varsa (2000) also found yield reductions for soybean in Illinois with spring applications of high K fertilizer rates (112 and 168 kg K ha\(^{-1}\)) and attributed yield reduction possibly to salt injury. In our study, it is not clear what factor or factors might have contributed to the observed decline in yield. The fact that STDB produced greater yields compared to the two no-till treatments at each K fertilizer rate (including the check) further provides evidence that yield advantage with STDB is related to a tillage effect and not to placement of fertilizers. Further, whatever the cause for decline in yield with the higher K fertilizer rates in the no-till treatments, our data indicate that STDB seems to protect the crop from such negative effects.

We evaluated yield components from a limited number of treatments in an effort to further understand the effect of treatment on seed yield. While we observed that the differences in yield produced by the tillage/fertilizer placement treatments were not reflected in yield component analysis, we observed differences related to P and K fertilizer rate. The 4% yield increase observed as P fertilizer rate increased from no application to 36 kg P ha\(^{-1}\) yr\(^{-1}\) (Figure 2.1) was associated with a 6% increase in the number of pods plant\(^{-1}\) (data not shown). These data agree with findings by others that observed the largest increase in soybean yield in response to fertilizer application was the result of greater number of pods plant\(^{-1}\) (Board et al., 1999; Fernández et al., 2009). A 2% reduction in weight seed\(^{-1}\) was associated to the 4% reduction in seed yield measured for 168 kg K ha\(^{-1}\) yr\(^{-1}\) compared to no K application averaged across tillage/fertilizer placement treatment (Figure 2.2). Again, it is not clear what factors might have influenced seed weight to cause the observed decline in yield with high K fertilizer rate.
Soybean seed P and K accumulation was significantly affected by tillage/fertilizer placement treatment, while seed P and K concentrations were not affected by tillage/fertilizer placement treatment (Table 2.2). Further analysis indicated that STDB accumulated greater amounts of P and K in seed compared to the no-till treatments in direct proportion to the seed yield increase observed in response to the tillage/fertilizer placement treatment (Table 2.3). Similarly, P fertilizer rate increased seed P and K accumulation (Table 2.2) as a direct result of the seed yield increase produced by increasing P fertilizer rate (Figure 2.1). While P fertilizer rate increased seed P concentration from 5.49 g P kg\(^{-1}\) for the 0 kg P ha\(^{-1}\) yr\(^{-1}\) rate to 5.81 g P kg\(^{-1}\) for the 36 kg P ha\(^{-1}\) yr\(^{-1}\) rate and K fertilizer rate increased seed concentration from 20.20 g K kg\(^{-1}\) for the 0 kg K ha\(^{-1}\) yr\(^{-1}\) rate to 20.86 g K kg\(^{-1}\) for the 168 kg K ha\(^{-1}\) yr\(^{-1}\) rate, the differences were not sufficiently large to increase nutrient accumulation beyond the response observed for seed yield to P and K fertilizer rate. There were no meaningful two- or three-way interactions for seed P and K parameters (Table 2.2).

We observed no response to tillage/fertilizer placement treatment in P and K concentrations in fully developed top trifoliate leaves at R1, but concentrations of all essential plant nutrient were within the sufficiency range of soybean as reported by Small and Ohlrogge (1973) (data not shown). While trifoliate leaf P concentrations were within the sufficiency range, we observed a linear response in leaf P concentration to P fertilizer rate (Figure 2.3). The increase in leaf P concentration with increasing P fertilizer rate was correlated (R\(^2\)=0.58) with an increase in soybean seed yield. While this is a limited study (only three years and one location), these data call into question whether sufficiency values reported in the literature (Small and Ohlrogge, 1973, Munson and Nelson, 1990)
and recommended in Illinois (Fernández and Hoeft, 2009) are still adequate for current soybean production. Further, we observe that trifoliate leaf P concentration was highly correlated to seed P concentration ($R^2=0.94$) (Figure 2.4a) and accumulation ($R^2=0.93$) (Figure 2.4b). Seed P accumulation was increased from 15.5 kg P ha$^{-1}$ with the 0 kg P ha$^{-1}$ yr$^{-1}$ rate to 17.2 kg P ha$^{-1}$ with the 36 kg P ha$^{-1}$ yr$^{-1}$ rate. The high correlation with trifoliate leaf P concentration suggests that trifoliate leaf analysis at R1 stage could reasonably predict P concentration and total accumulation of seed at harvest.

Trifoliate leaf K concentrations were within the sufficiency range, but there was a positive linear response to K fertilizer rate (Figure 2.5). We also observed trifoliate leaf K concentrations was highly correlated to seed K concentration ($R^2=0.98$) [Seed K concentration = 13.899 + 0.1015 * (Trifoliate K)]. Unlike for P, however, the increase in trifoliate leaf K concentration was not accompanied by an increase in seed yield or seed K accumulation. Numerous studies have reported similar results when soil test levels exceed requirements to maximize yield (Hanway and Weber, 1971; Ebelhar and Varsa, 2000; Fernández et al., 2009).

While not a focus of the study, we observed secondary effects of K treatment in which the increase in leaf K levels with increasing K fertilizer rates was accompanied by decreasing leaf nitrogen (N) and magnesium (Mg) concentrations and increasing manganese (Mn) concentrations (Figure 2.6). The antagonistic relationship between K and Mg uptake is well known (Marschner, 1995). This reduction in Mg levels in tissue is probably related to surplus K$^+$ ions in the soil that reduce the uptake potential of Mg$^{2+}$ ions competing for the same non-selective cation channels (Shabala and Hariadi, 2005). The reduction of N in tissue with K fertilizer rate might be related to an increase in
chloride ion (Cl\(^-\)) concentrations resulting from KCl fertilizer applications which are known to reduce nitrate (NO\(_3^-\)) accumulation in vegetative tissues (Xu et al., 2000, Umar and Iqbal, 2009). These changes in concentration presented in Figure 2.6 were not evaluated in detail, and we can only speculate that they might be related to the slight seed yield reduction observed with K fertilizer rate.

Deep banding of K (NTDB and STDB) over a three-year period significantly increased soil K test levels at the 10 to 18 cm soil depth increment compared to initial (pre-fertilizer treatment application) conditions (Table 2.5). Similar results were observed for soil P test levels with P banding, though STDB only showed a trend. Due to large variability in soil test results it was difficult to establish significant differences, but the decreasing trends in P and K levels in the 0 to 5 cm layer of the deep banding treatments (NTDB and STDB) was likely the result of nutrient uptake by the crop without replenishment by fertilizer application in that layer. On the other hand, trends in test levels in the surface layer for NTBC showed that broadcast fertilizer applications were nearly maintaining or slightly increasing fertility levels. Initial soil P test levels showed vertical stratification with greater concentrations on the surface (Table 2.6). For K, initial soil test levels were also vertically stratified within the top 18 cm, but the 18 to 50 cm layer had similar levels to the 5 to 10 cm layer. Compared to starting soil test levels, when no fertilizer was applied over the three-year period of the study, soil P levels were reduced two fold in the surface layer and a similar trend was observed for K (Table 2.6). Relative to starting conditions at the 10 to 18 cm depth, when P was applied soil P test levels more than double, and when K was applied soil K test levels increased by 68%. These increases were a direct response of subsurface band fertilizer applications. It is not
clear why K test levels at the 5 to 10 cm depth increased for the 168 kg K ha\(^{-1}\) yr\(^{-1}\) rate. While we observed that impact on seed yield was the result of tillage effect and not fertilizer placement (Table 2.4), these soil test data indicate that fertilizer placement of slow-mobile nutrients, such as P and K, can result in substantial changes in soil test levels over a short period of time. Further, we speculate the changes in P and K soil test levels would have been even more distinct if the treatments would have been established for a longer period of time.

**CONCLUSIONS**

Averaged over fertilizer P and K fertilizer rates, STDB produced greater seed yields than NTDB which in turn had slightly greater yields than the NTBC treatment. The yield difference was likely the result of improved soil conditions, including greater water content, for soybean production with strip-till compared to the no-till treatments. There was an increase in trifoliate leaf P concentration and seed yield in response to P fertilizer rate. We also observed that yield increase with increasing P fertilizer rate was the result of greater number of pods plant\(^{-1}\). The response to P fertilizer rate, however, was uniform across tillage/fertilizer placement treatments, indicating that fertilizer rate cannot be reduced with deep banding relative to broadcasting without a reduction in seed yield. Accumulation of K in the trifoliate increased linearly with K fertilizer rate but did not translate into increased seed yield. There was a significant tillage/fertilizer placement by K interaction indicating that high K fertilizer rates slightly reduced seed yields in the no-till treatments, but there was no effect with STDB. While it is not clear why this slight reduction occurred, our data indicate that STDB seems to lessen this adverse effect. Tillage/fertilizer placement produced no effect on seed P and K concentrations but P and
K accumulation was increased for STDB relative to the no-till treatments as a direct response to seed yield increase in STDB. On the other hand, seed P and K concentration were increased by P and K fertilizer application, respectively. Also, seed concentrations were well correlated to concentrations in trifoliate tissues at R1 development stage, suggesting that trifoliate nutrient analysis may be a viable way to predict seed P and K concentrations, at least under similar conditions present in this study. Sub-surface banding P and K over a three-year period increased soil test levels at the point of fertilizer application and provides evidence that agronomic P and K fertilizer rates applied in a band can result in substantial changes in soil test levels over a short period of time. The study clearly indicates that improved soybean production was the result of a tillage effect with STDB relative to the no-till treatments and P and K placement had no effect on soybean yield.

ACKNOWLEDGMENTS

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REFERENCES


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TABLE 2.1. Growing season monthly precipitation, number of days with rain, and air temperatures for 2007 to 2009 and departure from the 30-yr mean for Champaign, IL.

<table>
<thead>
<tr>
<th>Month</th>
<th>Year</th>
<th>Precipitation</th>
<th>Rain</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mm</td>
<td>days</td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>May</td>
<td>2007</td>
<td>41(-83)†</td>
<td>8(-4)</td>
<td>27.1(3.9)</td>
<td>13.0(2.1)</td>
<td>20.1(3)</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>154(30)</td>
<td>15(3)</td>
<td>20.4(-2.7)</td>
<td>8.9(-2)</td>
<td>14.7(-2.4)</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>145(21)</td>
<td>14(2)</td>
<td>23.3(0.1)</td>
<td>11.4(0.5)</td>
<td>17.4(0.3)</td>
</tr>
<tr>
<td>June</td>
<td>2007</td>
<td>144(39)</td>
<td>11(1)</td>
<td>29.1(1)</td>
<td>16.9(0.7)</td>
<td>23.1(0.9)</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>163(57)</td>
<td>11(1)</td>
<td>28.6(0.4)</td>
<td>17.2(1)</td>
<td>22.9(0.7)</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>112(7)</td>
<td>14(4)</td>
<td>29.2(1)</td>
<td>18.1(1.9)</td>
<td>23.7(1.5)</td>
</tr>
<tr>
<td>July</td>
<td>2007</td>
<td>87(-30)</td>
<td>10(0)</td>
<td>28.4(-1.2)</td>
<td>17.0(-1.2)</td>
<td>22.7(-1.2)</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>200(83)</td>
<td>15(5)</td>
<td>28.8(-0.8)</td>
<td>17.6(-0.6)</td>
<td>23.2(-0.7)</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>160(43)</td>
<td>12(2)</td>
<td>26.2(-3.4)</td>
<td>16.0(-2.2)</td>
<td>21.1(-2.8)</td>
</tr>
<tr>
<td>August</td>
<td>2007</td>
<td>38(-64)</td>
<td>8(-2)</td>
<td>31.6(2.8)</td>
<td>19.7(2.5)</td>
<td>25.7(2.7)</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>20(-82)</td>
<td>9(-1)</td>
<td>28.0(-0.7)</td>
<td>16.5(-0.7)</td>
<td>22.3(-0.7)</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>143(41)</td>
<td>12(2)</td>
<td>26.9(-1.8)</td>
<td>15.4(-1.7)</td>
<td>21.2(-1.8)</td>
</tr>
<tr>
<td>September</td>
<td>2007</td>
<td>52(-27)</td>
<td>7(-1)</td>
<td>28.9(3.2)</td>
<td>14.2(1.6)</td>
<td>21.6(2.4)</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>207(127)</td>
<td>11(3)</td>
<td>25.3(-0.4)</td>
<td>14.1(1.5)</td>
<td>19.7(0.5)</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>20(-59)</td>
<td>7(-1)</td>
<td>24.7(-1)</td>
<td>13.9(1.3)</td>
<td>19.3(0.2)</td>
</tr>
<tr>
<td>October</td>
<td>2007</td>
<td>84(0)</td>
<td>9(-1)</td>
<td>21.6(3.2)</td>
<td>9.4(3.3)</td>
<td>15.5(3.3)</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>75(-9)</td>
<td>6(-4)</td>
<td>19.2(0.8)</td>
<td>6.1(0)</td>
<td>12.7(0.4)</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>223(140)</td>
<td>20(11)</td>
<td>14.4(-3.9)</td>
<td>5.3(-0.8)</td>
<td>9.9(-2.4)</td>
</tr>
</tbody>
</table>

Table 2.2. Analysis of variance for soybean seed yield and seed phosphorus (P) and potassium (K) concentration and accumulation averaged over three years (2007-2009).

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>df†</th>
<th>Seed yield</th>
<th></th>
<th>Seed phosphorus concentration</th>
<th></th>
<th>Seed potassium concentration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>Pr &gt; F</td>
<td>F</td>
<td>Pr &gt; F</td>
<td>F</td>
<td>Pr &gt; F</td>
</tr>
<tr>
<td>Tillage/fertilizer placement (T)</td>
<td>2</td>
<td>38.93</td>
<td>0.002</td>
<td>2.02</td>
<td>0.248</td>
<td>10.81</td>
<td>0.024</td>
</tr>
<tr>
<td>Phosphorus fertilizer rate (P)</td>
<td>3</td>
<td>7.44</td>
<td>0.002</td>
<td>6.10</td>
<td>0.005</td>
<td>13.20</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>T × P</td>
<td>6</td>
<td>2.02</td>
<td>0.115</td>
<td>2.31</td>
<td>0.079</td>
<td>1.23</td>
<td>0.334</td>
</tr>
<tr>
<td>Potassium fertilizer rate (K)</td>
<td>3</td>
<td>4.84</td>
<td>0.003</td>
<td>10.31</td>
<td>&lt;.001</td>
<td>0.44</td>
<td>0.724</td>
</tr>
<tr>
<td>T × K</td>
<td>6</td>
<td>2.06</td>
<td>0.058</td>
<td>1.78</td>
<td>0.102</td>
<td>1.80</td>
<td>0.099</td>
</tr>
<tr>
<td>P × K</td>
<td>9</td>
<td>0.74</td>
<td>0.669</td>
<td>1.14</td>
<td>0.335</td>
<td>1.34</td>
<td>0.214</td>
</tr>
<tr>
<td>T × P × K</td>
<td>18</td>
<td>0.97</td>
<td>0.497</td>
<td>1.19</td>
<td>0.270</td>
<td>0.61</td>
<td>0.895</td>
</tr>
</tbody>
</table>

† Numerator degrees of freedom from Type III sum of squares.
Table 2.3. Soybean seed yield and seed phosphorus (P) and potassium (K) concentration and accumulation as affected by tillage/fertilizer placement [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)] averaged over three years (2007-2009) and P and K fertilizer rates.

<table>
<thead>
<tr>
<th>Tillage/fertilizer placement</th>
<th>Seed yield</th>
<th>Seed phosphorus</th>
<th>Seed potassium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha⁻¹</td>
<td>Concentration</td>
<td>accumulation</td>
</tr>
<tr>
<td>NTBC</td>
<td>2.77 c†</td>
<td>5.69 a</td>
<td>15.8 b</td>
</tr>
<tr>
<td>NTDB</td>
<td>2.87 b</td>
<td>5.56 a</td>
<td>15.9 b</td>
</tr>
<tr>
<td>STDB</td>
<td>3.06 a</td>
<td>5.81 a</td>
<td>17.7 a</td>
</tr>
</tbody>
</table>

† Same letters within a column indicates no significant differences between means due to tillage/fertilizer placement.
Table 2.4. Seed yield differences calculated from the mean contrast estimates for the unfertilized plots (0 kg P ha\(^{-1}\) yr\(^{-1}\) and 0 kg K ha\(^{-1}\) yr\(^{-1}\)) for the different tillage/fertilizer placement treatments [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)] averaged across three years (2007-2009).

| Contrast          | Yield difference (Mg ha\(^{-1}\)) | Standard error | Pr > |t| |
|-------------------|-----------------------------------|----------------|------|---|
|                   |                                   | No P application | No K application |       |
| NTBC-NTDB         | -0.04                             | 0.06            | 0.54 |
| NTDB-STDB         | -0.33                             | 0.06            | <0.01|   |
| NTBC-STDB         | -0.37                             | 0.06            | <0.01|   |
Table 2.5. Change (Δ) in soil phosphorus (P) and potassium (K) concentration over a three-year period between pre-fertilizer treatment application (initial conditions) and fall 2009 at different soil depth increments as affected by tillage/fertilizer placement treatment [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)] averaged over P and K fertilizer rates.

<table>
<thead>
<tr>
<th>Soil depth cm</th>
<th>Δ soil test P kg P ha⁻¹</th>
<th>Δ soil test K kg K ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>-5.4 NTBC, -20.3 NTDB, -17.1 STDB</td>
<td>23.3 NTBC, -33.5 NTDB, -28.3 STDB</td>
</tr>
<tr>
<td>5-10</td>
<td>-2.2 NTBC, -3.3 NTDB, -2.3 STDB</td>
<td>45.9* NTBC, 33.8 NTDB, 45.2 STDB</td>
</tr>
<tr>
<td>10-18</td>
<td>-1.2 NTBC, 6.4* NTDB, 7.0 STDB</td>
<td>15.9 NTBC, 46.8* NTDB, 51.7* STDB</td>
</tr>
<tr>
<td>18-50</td>
<td>-0.5 NTBC, 0.5 NTDB, 0.3 STDB</td>
<td>-3.3 NTBC, 10.3 NTDB, 9.5 STDB</td>
</tr>
</tbody>
</table>

Data are back-transformed means from natural log-transformed data.

* Indicate significant change in concentration from initial conditions within a particular tillage/fertilizer placement treatment and soil depth increment.
Table 2.6. Soil test phosphorus (P) and potassium (K) levels as affected by P fertilizer rate (0 and 36 kg P ha\(^{-1}\) yr\(^{-1}\)) and K fertilizer rate (0 and 168 kg K ha\(^{-1}\) yr\(^{-1}\)) measured in 2007 prior to fertilizer treatment application (initial conditions) and in fall 2009 at different soil depth increments averaged over three tillage/fertilizer placement treatments.

<table>
<thead>
<tr>
<th>Soil depth</th>
<th>Soil test P</th>
<th>Soil test K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0P</td>
<td>36P</td>
</tr>
<tr>
<td>cm</td>
<td>kg P ha(^{-1})</td>
<td>kg K ha(^{-1})</td>
</tr>
<tr>
<td>0-5</td>
<td>39 a† 18 a*</td>
<td>40 a 33 a</td>
</tr>
<tr>
<td>5-10</td>
<td>16 b 11 b</td>
<td>17 b 18 b</td>
</tr>
<tr>
<td>10-18</td>
<td>9 c 7 c</td>
<td>10 c 23 ab*</td>
</tr>
<tr>
<td>18-50</td>
<td>4 d 3 d</td>
<td>4 d 5 c</td>
</tr>
</tbody>
</table>

Data are back-transformed means from natural log-transformed data.
† Same letters within a column indicates no significant differences between means due to soil depth within each P and K fertilizer rate and sampling time.
* Indicate significant difference between means due to different sampling times within each P and K fertilizer rate.
Figure 2.1. Soybean seed yield as affected by phosphorus (P) fertilizer rate averaged over three years (2007-2009), tillage/fertilizer placement, and potassium fertilizer rates. [Seed yield = 2.8265 + 0.004 * (P rate), R² = 0.83, P = 0.088].
Figure 2.2. Soybean seed yield as affected by tillage/fertilizer placement [no-till/broadcast (NTBC), no-till/deep band (NTDB) and strip-till/deep band (STDB)] and potassium (K) fertilizer rate averaged over three years (2007-2009) and phosphorus fertilizer rates. [Seed yield_{NTBC} = 2.8116 - 0.0005 \times (K \text{ rate}), R^2 = 0.76, P = 0.1307; Seed yield_{NTDB} = 2.9452 - 0.0011 \times (K \text{ rate}), R^2 = 0.99, P = 0.007; Seed yield_{STDB} = 3.0594 - 0.00005 \times (K \text{ rate}), R^2 = 0.05, P = 0.920].
Figure 2.3. Soybean trifoliate leaf phosphorus (P) concentration at R1 development stage as affected by P fertilizer rate averaged over three years (2007-2009), tillage/fertilizer placement, and K fertilizer rates. [P concentration in leaves = 5.2174 + 0.0072 * (P rate), R² = 0.85, P = 0.077)].
Figure 2.4. Seed phosphorus (P) concentration (a) and accumulation (b) measured at seed harvest as affected by trifoliolate leaf P concentration measured at R1 development stage averaged over three years (2007-2009). [Seed P concentration = -0.01 + 1.0674 * (Trifoliolate leaf P concentration), $R^2 = 0.94$, $P = 0.029$; Seed P accumulation = -13.786 + 5.6539 * (Trifoliolate leaf P concentration), $R^2 = 0.93$, $P = 0.036$].
Figure 2.5. Soybean trifoliate leaf potassium (K) concentration at R1 development stage as affected by K fertilizer rate averaged over three years (2007-2009), tillage/fertilizer placement, and P fertilizer rates. [K concentration in leaves = 27.149 + 0.0123 * (K rate), $R^2 = 0.93$, $P = 0.033$].
Figure 2.6. Soybean trifoliate leaf magnesium (Mg), manganese (Mn), and nitrogen (N) relative concentrations at R1 development stage as affected by potassium (K) fertilizer rate averaged over three years (2007-2009), tillage/fertilizer placement, and P fertilizer rates. [Relative-concentration\textsubscript{Mg} = 97.6 - 0.0660 * (K rate), R\textsuperscript{2} = 0.81, P = 0.099; Relative-concentration\textsubscript{Mn} = 92.2 + 0.0483 * (K rate), R\textsuperscript{2} = 0.88, P = 0.060; Relative-concentration\textsubscript{N} = 99.6 - 0.0218 * (K rate), R\textsuperscript{2} = 0.91, P = 0.044].
CHAPTER 3

DISTRIBUTION OF SOYBEAN ROOTS, SOIL WATER, PHOSPHORUS AND POTASSIUM CONCENTRATIONS WITH BROADCAST AND SUBSURFACE-BAND FERTILIZATION

(Under review in Soil Sci. Soc Am. J.)

ABSTRACT

In conservation tillage fertilizer placement is designed to improve nutrient availability. Our objective was to determine the effect of tillage (no-till and strip-till) and P and K rate and placement on the distribution of soybean [Glycine max (L.) Merr.] roots and on water, P, and K levels in soil. A three-year field experiment was conducted near Urbana, Illinois with soybean following corn (Zea mays L.). Rates of 0-0, 36-0, 0-168, and 36-168 kg P-K ha⁻¹ yr⁻¹ were applied as no-till/broadcast (NTBC), no-till/deep band (15 cm beneath the planted row) (NTDB), and strip-till/deep band (STDB). Roots, soil water, P, and K levels were measured periodically at in-row (IR) and between-rows (BR) positions at 0 to 5, 5 to 10, 10 to 20, and 20 to 40 cm depths. Deep banding increased P and K test level beneath the row and lowered soil surface test-values compared to broadcast applications, but had no effect on root distribution. Compared to NTBC and NTDB, STDB had a 20% increase in soil water content during the seed-fill period at BR within the top 10 cm of soil where greatest apparent nutrient uptake (estimated by changes in soil-test) occurred. Within that zone, NTBC produced and maintained a larger root system than STDB, but STDB had 23% greater P and 30% greater K accumulation in shoots, greater apparent nutrient uptake and greater apparent nutrient uptake rate per unit of root surface area. The results indicate that STDB provides overall better soil conditions for P and K uptake compared to the NTBC and NTDB systems.
INTRODUCTION

Method of application of slowly-mobile nutrients such as P and K can be an important consideration in conservation tillage systems in which little or no soil mixing occurs. In such systems, recurring surface application of P and K results in vertical stratification of these nutrients in the soil, with higher concentrations in the surface layer than deeper in the profile (Buah et al., 2000). This stratification is also the result of the re-distribution of P and K as they are taken up by crops from the subsurface and deposited on the soil surface in the form of crop residue (Karlen et al., 1991; Robbins and Voss, 1991; Holanda et al., 1998; Vyn et al., 2002).

Different nutrient placement techniques for conservation tillage systems have been developed as a mechanism to improve nutrient availability or to increase fertilizer use efficiency. An early review by Randall and Hoeft (1988) indicated that banding P and K fertilizer in soils with low fertility can result in increased fertilizer use efficiency, profit, and yield compared to broadcast applications. Additionally, alternative nutrient placement techniques to broadcast applications have been developed to reduce vertical stratification of nutrients because of environmental concerns. High P levels in the soil surface can increase the risk of environmental degradation if P runs off from fields into rivers and lakes (McIsaac et al., 1995). In recent years, deep banding of P has been used as a way to lower surface P test levels and to reduce the potential for P runoff —and possibly environmental degradation— (Randall and Vetsch, 2008).

A potential drawback of continual deep banding of P and K fertilizer, however, is the subsequent repeating pattern of high and low test values that develops across the field. This repeating pattern
can increase variability and reduce our ability to accurately assess P and K fertility (Rehm, 1995; Mallarino and Borges, 2006).

As pointed out in a review by Randall and Hoeft (1988) and as evident by several more recent studies (Vyn and Raimbault, 1992; Bordoli and Mallarino, 1998; Mallarino et al., 1999; Vetsch and Randall, 2002) research on nutrient placement in conservation tillage systems has been focused mostly on corn production. Fewer studies have been devoted to compare the response of soybean to deep band and broadcast P and K applications. Further, these studies have produced inconsistent results on the effect of nutrient placement under conservation tillage systems. Some have reported greater soybean seed yield with deep band applications relative to broadcast applications (Hairston et al., 1990; Yin and Vyn, 2003), while others have observed no differences (Borges and Mallarino, 2000; Buah et al., 2000; Ebelhar and Varsa, 2000; Yin and Vyn, 2002).

The inconsistent response of soybean to P and K placement may be related to field conditions that limit nutrient availability. Soybean plants take up about 75% of their total P and K during the reproductive stages of development (Hanway and Weber, 1971). Low rainfall during the latter portion of the growing season, when evapotranspiration is typically high, can cause excessive dryness in the nutrient-rich soil surface. Excessive dryness in the surface layer can potentially limit root activity and reduce nutrient uptake (Bordoli and Mallarino, 1998; Borges and Mallarino, 2000; Buah et al., 2000; Yin and Vyn, 2003). Subsurface application of P and K into a soil zone with presumably greater water availability has been suggested as a way to lessen such an effect (Borges and Mallarino, 2000; Yin and Vyn, 2002).

In recent years strip-till has been proposed as a tillage system to deep-band nutrients and also to produce crop residue-free planting rows. This tillage system allows greater uniformity
and ease of planting and better soil moisture and temperature conditions for seed germination early in the growing season (Vyn and Raimbault, 1992; Jones et al., 1994; Morrison, 2002). Improved soil conditions with strip-till relative to no-till have been shown to increase soybean seed yield (Vyn et al., 1998; Farmaha et al., 2011). However, root interactions with nutrient placement or nutrient uptake mechanisms in no-till and strip-till systems are poorly understood (Fernández et al., 2009; Farmaha et al., 2011).

Localized P concentrations can induce root proliferation in the fertilizer band (Robinson, 1996) leading to greater water extraction (Gardner, 1964) and improved P and K uptake (Karunaratne et al., 1986). At the same time, subsurface P and K applications may force nutrient uptake deeper in the soil profile where there is less oxygen, which can reduce root activity (Barber, 1995). Fernández et al. (2008, 2009) showed that vertical stratification of K may enhance soybean yield because apparent K uptake, water availability, and root density were greater in the top 5 cm of the soil compared to deeper layers in a no-till field. Fernández et al. (2011) also showed that temporary asynchrony of soil K and soil water availability may not be a limiting factor for soybean production because dry periods in much of the US Midwest are typically short. Despite the importance of soil water and roots for nutrient uptake, they have not been studied to more clearly identify the potential benefits or drawbacks to deep banding. Further, to our knowledge, no research has been conducted to characterize soil water and soybean root proliferation in strip-till systems.

The objective of this study was to determine the effect of tillage (no-till and strip-till) and P and K fertilizer rate and placement on the distribution of soybean roots and on water, P, and K levels in soil.
MATERIALS AND METHODS

Site Description

Field experiments were conducted over a three-year period (2007 through 2009 growing seasons) at the Crop Sciences Research & Education Center near Urbana, Illinois on a Flanagan silt loam soil (Fine, smectitic, mesic Aquic Argiudolls) intermixed with small areas of Drummer silty clay loam soil (Fine-silty, mixed, superactive, mesic Typic Endoaquolls). The critical soil test levels for the study site, defined as the point at which near maximum yields are achieved, are 20 mg P kg\(^{-1}\) and 150 mg K kg\(^{-1}\) for the top 18 cm sampling depth (Fernández and Hoeft, 2009). Pre-treatment soil test values in the top 18 cm of soil were: Bray P\(_1\) (Bray and Kurtz, 1945) 20 mg kg\(^{-1}\) and 1 \(M\) \(\text{NH}_4\text{OAc}\) extractable K (Warncke and Brown, 1998) 167 mg kg\(^{-1}\). For additional soil test information see Farmaha et al. (2011).

The year prior to the study the field was chisel-plowed and planted with corn. The study was conducted on a corn-soybean rotation with both crops present every year. The study was set up as a split-split-plot arrangement in a randomized complete-block design with three replications. The main (whole) plot included three tillage/fertilizer placement treatments: no-till/broadcast (NTBC); no-till/deep band (NTDB); and strip-till/deep band (STDB). The split-plot treatments were four P application rates (0, 12, 24, and 36 kg P ha\(^{-1}\) yr\(^{-1}\)), and the split-split plot treatments were four K application rates (0, 42, 84, and 168 kg K ha\(^{-1}\) yr\(^{-1}\)). Treatments were applied approximately a month prior to planting. Broadcast treatments were applied by hand using a spin-spreader. The NTBC treatment had no soil disturbance prior to planting. Deep banding of fertilizer was 15 cm below the surface at crop-row position and applied with a Gandy Orbit Air applicator (Model 6212C). The NTDB treatments were applied using 2 cm wide, low-disturbance, modified ammonia knives that caused negligible movement of surface residue and
disturbed a band of soil about 15 cm deep and 2 cm wide at the bottom and 4 cm wide at the surface. The STDB treatments were applied with a unit consisting of a wavy cutting coulter and row cleaners in front of modified ammonia mole knives, with closing discs behind the knives that disturbed the soil in an area about 17 cm deep, 4 cm wide at the bottom and produced a 5 to 8 cm tall by 25 cm wide berm. For a more detailed description on experimental setup and management practices see Farmaha et al. (2011).

In-season soil, soybean-root, and above-ground vegetative samples were collected from all the tillage/fertilizer placement treatments but restricted to a subset of fertilizer rates representing the combination of lowest and highest applications (0-0, 36-0, 0-168, and 36-168 kg P-K ha\(^{-1}\) yr\(^{-1}\)). For P and K analysis, a three-composite core soil sample was collected at growth stage R1 (Ritchie et al., 1994) from in-row (IR) and between-rows (BR) positions using a hand-held, 2.5-cm diameter probe. Cores were divided into 0 to 5, 5 to 10, 10 to 20, and 20 to 40 cm depth increments. In 2008 and 2009 soil samples were also collected at the R3 development stage. Separate root samples were collected at the same time and in the same fashion as soil samples. All above-ground vegetative tissues were collected at R1 development stage from all plants growing in the same 66 cm by 76 cm area in which soil and root samples were collected.

Above-ground vegetative samples were dried in a forced-air oven at 60°C at least for 72 hrs. to achieve constant weight, weighed, and ground to pass a 1-mm mesh screen on a Wiley mill (Standard Model 3; Arthur H. Thomas Co., Philadelphia, PA). The ground tissue was analyzed for nutrient content by A & L Great Lakes Laboratories, Inc., Fort Wayne, IN following the official methods of analysis of AOAC International (Horwutz, 2000).

Soil samples were air dried, ground with a Dynacrush mill (Custom Laboratory Equipment Inc., Orange City, FL, USA), to pass through a 2 mm diameter sieve, and analyzed
for plant-available P with the Bray P\textsubscript{1} extract (Bray and Kurtz 1945) and for plant-available K with the M NH\textsubscript{4}OAc extract (Warncke and Brown, 1998).

Roots were separated from the soil with a semiautomatic hydro-pneumatic elutriation system (Gillison’s Variety Fabrication, Inc., Benzonia, MI, USA) and roots were collected in 410 µm sieves (Smucker et al., 1982). The content of the sieve was then transferred into a shallow tray where organic debris (including dead roots that by the amount of decay were clearly not from the growing crop) 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., Quebec, Canada).

Soil water content was monitored continuously, and daily averages calculated, during the growing season using ECH\textsubscript{2}O EC-5 and EC-20 moisture probes and Em-50 digital data loggers (Decagon Devices Inc.). The soil probe data were checked against calibration measurements taken during the growing season. Soil moisture probes were installed at the 0 to 5, 5 to 10, 10 to 15, 15 to 20, and 20 to 40 cm soil depth increments at IR and BR positions in all tillage/fertilizer placement treatments receiving 36-168 kg P-K ha\textsuperscript{-1} yr\textsuperscript{-1} rate.

**Statistical Analysis**

Soybean data were analyzed with the MIXED procedure of SAS (SAS Institute, 2009), with year, block, and their interactions with main treatments considered random. Residuals for all analyses of variance were evaluated for normality based on the Shapiro-Wilk test in the UNIVARIATE procedure of SAS (SAS Institute, 2009) while homogeneity of variances was examined visually from the residual plots (plot the residuals versus fitted values). Soil nutrient,
root, and soil water data were modeled as repeated measures with the appropriate covariance structure. Soil depth was considered as repeated measures for soil nutrient and root data analyses while soil depth and time were considered as repeated measures for soil water data. Soil and root data were subjected to log-normal transformation to meet the criterion of common variance. Means and standard errors of the log-normal transformed data were back-transformed using the MMAOV macro (Saxton, 1998). Soil water data models were restricted up to two level interactions of the main effects to meet the convergence criteria. Means comparison tests were done following the Tukey’s studentized range honestly significant difference (HSD) test to control experiment-wise error and with Tukey-Kramer test for unbalanced data. Treatment effects were declared significant at an alpha level of ≤ 0.1.

RESULTS AND DISCUSSION

The complete analysis of seed yield data for this study was reported by Farmaha et al. (2011). We reported there that averaged across all three years, STDB yielded 3.06 Mg ha\(^{-1}\), a yield increase of 10% relative to NTBC and of 7% relative NTDB. Seed yield showed a linear increase with P fertilization with the 0 kg P ha\(^{-1}\) yr\(^{-1}\) rate producing 2.84 Mg ha\(^{-1}\) and the highest rate of 36 kg P ha\(^{-1}\) yr\(^{-1}\) rate producing 2.96 Mg ha\(^{-1}\). No yield increase was observed in response to K fertilizer rate.

Soil Water Content

Averaged over the growing season, soil water content was lower in 2007 than in 2008 and 2009 (Figure 3.1). There were 34 days during 2007 when the soil water content was 20% or less, but there were no days during the 2008 and 2009 seasons when soil was this dry. Except for a few periods in August 2008 and September 2009, rainfall was well-distributed, but amounts were lower in 2007. Averaged over years, soils in the BR position had greater water content than
did those in the IR position. The difference between crop-row positions was accentuated with drier conditions, as observed for 2007.

In general, soil water content increased with increasing soil depth (Figure 3.2). Until approximately the middle of August soil water content at the IR position was greater for NTBC than STDB for all soil depth increments within the top 15 cm and for the 5 to 10 and 10 to 15 cm depth in NTDB. Lower soil water content where fertilizer was deep-banded may be the result of soil disturbance during fertilization and greater water evaporation as the soil was exposed to sunlight until soybean canopy covered the soil surface. Further, throughout the growing season the NTBC treatment had greater soil water content at IR for the 20 to 40 cm layer compared to NTDB and STDB, at BR for the 15 to 20 cm compared to NTDB and STDB, and at BR for the 10-15 cm depth compared to STDB (Figure 3.2). It is not clear what cause these differences. A possible explanation is that there was less water uptake by soybeans in NTBC compared to the NTDB and STDB treatments, but that does not explain the differences early in the growing season when water uptake by the crop is normally low and likely roots have not reached deep in the soil. Averaged across the growing seasons a significant three-way interaction ($P < 0.001$) of tillage/fertilizer placement by position with respect to the crop-row by soil depth was explained by a lack of difference between IR and BR in the NTBC and NTDB treatments at the 0 to 5 and 5 to 10 cm depths, whereas the BR position contained greater soil water for the STDB treatment. Within the top 5 cm of soil, the BR position had 10% greater soil water content in STDB than in the no-till systems (NTBC and NTDB). Similar soil water content differences were observed in the 5 to 10 cm depth increment of the soil. These differences were enlarged during the seed-fill period (R5-R6) when soybean dry biomass and nutrients accumulate quickly and water demands are large (Ritchie et al., 1994). During this critical period, compared to the no-till systems, soil
water content at the BR position in STDB was 21% greater in the 0 to 5 cm depth and 18% greater in the 5 to 10 cm depth (Table 3.1). During the seed-fill period, there were significant differences in soil water content due to tillage/fertilizer placement treatment below the 5 to 10 cm depth, but there was not a consistent pattern.

Greater soil water content within the top 10 cm of soil at BR position in STDB relative to no-till treatments (Table 3.1 and Figure 3.2) is likely the result of greater water infiltration and percolation resulting from the tillage operation in STDB. Lipiec et al. (2006) indicated that tillage can increase water infiltration and storage capacity relative to undisturbed soils in no-till. While strip-till disturbs crop residue in the tillage strip, crop residue in the BR position is left undisturbed similar to no-till systems. Crop residue can further help maintain soil water content by reducing evaporation and surface water runoff (Vyn et al., 1998). Protection against evaporative losses may be especially important at BR position in the early vegetative stages of development when crop canopy is small and the soil is exposed to greater solar radiation. It is possible that greater soybean seed yields with STDB may have resulted from greater soil water content near the soil surface which can improve nutrient uptake and plant growth (Barber, 1995; Fernández et al., 2011).

**Roots**

In the top 40 cm of the soil, weighted averages across fertilizer rates, crop-row positions, and development stages, showed that NTBC produced 14% greater RLD compared to STDB; NTDB produced intermediate values (Figure 3.3). Although somewhat complicated by a tillage/fertilizer placement by P and K fertilizer rate interaction, RSD showed a similar pattern to RLD when averaged across P and K fertilizer rate (data for stage R1 are shown in Table 3.2). For all tillage/fertilizer placement treatments, as the crop developed from R1 to R3 stage, soybean
RLD declined in the 0 to 5 cm depth but did not change in deeper soil layers at either the IR or BR position (Figure 3.3). Further, the three-way interaction tillage/fertilizer placement by soil depth by development stage was explained by a larger decline in RLD at the 0 to 5 cm depth at BR position for STDB compared to the no-till systems as plants developed from R1 to R3 stage ($P = 0.081$). The relatively greater decline in RLD for STDB compared to NTBC resulted in a 43% greater RLD at the 0 to 5 cm depth for NTBC compared to STDB at R3 development stage. Similarly, RSD at the 0 to 5 cm depth at R3 development stage in NTBC was 0.83 cm$^2$ cm$^{-3}$ and 41% greater relative to STDB. Ritchie et al. (1994) indicated that lateral soybean roots are present at BR position in 76-cm row-spacing typically by V6 development stage. Barber (1995) found younger roots are more active in nutrient uptake, more dynamic in growth and decay compared with older roots. The natural morphological tendency of soybean roots is to grow outward into the BR position and proliferate in surface layers rather than sub-surface layers of the soil (Barber, 1995). It follows that the BR position would likely be the area of greater root activity and possibly greater nutrient uptake. In this study NTBC induced greater root length growth and maintenance (less reduction in RLD between R1 and R3 development stage) compared to STDB (Figure 3.3). Other studies have observed root proliferation as a compensatory mechanism to obtain water or nutrients under stressful conditions, but this compensatory mechanism does not always result in improved seed yield (Porterfield, 2002; Fernández et al., 2011). Further, we found 9% greater mean root diameter (MRD) at the 0 to 5 cm depth at the BR position in STDB compared with NTBC (Figure 3.4). This depth and crop-row position also had greater soil water content under STDB than NTBC (Table 3.1, Figure 3.2). Under adequate nutrient conditions, plants allocate more energy to shoot growth and to increase root diameter (Powell, 1974) than to root length growth (Atkinson, 1973). The observed impact
of STDB on root parameters may be an indication that STDB improves conditions for nutrient availability compared to NTBC, and that these improved conditions may have resulted in overall greater seed yield.

Localized fertilizer placement produced no increase in RLD (Figure 3.3) or changes in MRD (Figure 3.4). A lack of soybean root growth in response to localized K is in agreement with other studies (Hallmark and Barber, 1984; Coale and Grove, 1986; Fernández et al., 2011). Conversely, soybean roots have been shown to respond to localized P fertility, but only under limited soil P test levels (Atkinson, 1973; Powell, 1974; Hallmark and Barber, 1984). In our study the initial soil P test level in the top 18 cm of the soil (20 mg P kg\(^{-1}\)) is not considered to be limiting, so the lack of response in root proliferation to localized P was not surprising. When soil fertility test values are at adequate levels (near the critical value) or higher, banding fertilizer may not improve nutrient availability as a result of greater root proliferation. Root length density was 16% greater at IR compared with the BR position. The decrease in RLD with increasing soil depth was similar regardless of position with respect to the crop-row (Figure 3.3). Greater RLD at IR relative to BR position was also observed by Hulugalle and Lal (1986) and illustrate typical soybean root development. The top 5 and top 10 cm of the soil surface had 47% and 76% of the measured RLD, respectively. In contrast, MRD was uniform across soil depth at the IR position but increased with increasing soil depth at the BR position (Figure 3.4). However, the magnitude of change in MRD was relatively minor; thus, calculated RSD reflected similar patterns to those observed for RLD and are not presented. Analysis of RLD at R3 development stage and 40-cm depth water content averaged across IR and BR at the pod-fill period (R3 to R4 development stages) showed a strong correlation [Soil water = -0.0064 x (RLD) + 0.2735; \(R^2 = 0.75\)] indicating that as RLD increased the amount of soil water decreased. Similar results were
observed for the R1 development stage. While it is possible that greater RLD enhanced water extraction, it is also possible that water evaporation from the soil surface and closer proximity to the water table of deeper soil layers may have also contributed to the increasing water content gradient with increasing soil depth.

The tillage/fertilizer placement by K fertilizer rate interaction resulted from the fact that RSD increased in response to application of 168 kg K ha\(^{-1}\) yr\(^{-1}\) in NTBC but not in STDB (Table 3.2). It is unlikely that this increase in RSD is in response to localized K fertility in the soil surface of the NTBC treatment. As indicated earlier, studies have shown that soybean roots do not proliferate in response to localized K, even in vertically stratified systems as in our study (Hallmark and Barber, 1984; Coale and Grove, 1986; Fernández et al., 2011). Farmaha et al. (2011) reported a 13% reduction in seed yield in NTBC relative to STDB for the 168 kg K ha\(^{-1}\) yr\(^{-1}\) rate. It is well established that root growth increases as a mechanism to compensate for stressful plant-growing conditions (Barber, 1995; Porterfield, 2002). Increased root growth along with a yield reduction in NTBC may be an indication that this is a more stressful system for soybean production compared to STDB. Further, averaged across P fertilizer rates, we found that STDB accumulated 23% more P in above-ground tissues than NTBC (Table 3.2). Similarly, above-ground tissue K accumulation increased with the application of K fertilizer, but soybean plants with STDB accumulated 30% more K than NTBC, while NTDB showed intermediate values. Since soybeans in STDB accumulated more K with a smaller root surface area than in NTBC, the estimated K uptake rate, or efficiency of nutrient uptake per unit of root surface area, was 67% greater in STDB than in NTBC. In NTDB estimated K uptake rates were intermediate and not significantly different than those in the other tillage/fertilizer placement treatments. Although only a trend, similar results were observed for P uptake rates (Table 3.2). Since P and
K uptake rates in NTDB were not different, but numerically closer to STDB than NTBC, we speculate that banding the fertilizer may be enhancing uptake to a greater extent than the broadcast application. However, if indeed banding enhances uptake, it is not because of greater root proliferation, as we already discussed. These findings provide additional evidence that STDB is providing overall better conditions for nutrient uptake than NTBC.

**Soil P and K**

Different tillage/fertilizer placement treatments produced similar declines in soil P test concentrations over the three years of this study in the 0 to 5 cm layer receiving no P fertilizer (Figure 3.5). Similarly, for the 0 to 5 cm layer receiving no K fertilizer there was a significant decline in soil K test levels ranging from 44 mg K kg\(^{-1}\) for NTBC to 58 mg K kg\(^{-1}\) for STDB. Compared to the surface layer, decline of soil P test levels in subsurface layers were small for all tillage/fertilizer placement treatments when no P was supplied (Figure 3.5). These declines, however, were significantly different from zero at all layers only in the STDB treatment. When no K was supplied, soil K data showed an inconsistent pattern for the different subsurface layers with overall no change in soil K test levels for all three tillage/fertilizer placement treatments (data not shown). The lack of significant differences in soil K in the subsurface was related to large variability in the data. Others have indicated similar difficulties in establishing changes in soil K test over time due to large variability (Randall et al., 1997; Mallarino and Borges, 2006).

At stage R1 for the 0 kg P ha\(^{-1}\) yr\(^{-1}\) rate, change in soil P test levels over the top 40 cm of the soil (Figure 3.5) was well correlated \((R^2=0.96)\) to total plant P uptake (Table 3.2). Similar analysis but for P removal in harvested seed over three years for the 0 kg P ha\(^{-1}\) yr\(^{-1}\) rate explained 86% of the variability in the observed change in soil P test levels over the top 40 cm of the soil at stage R1 \(\Delta P\) test level\(_{0\to 40\,\text{cm}}\) = 1.9851 x (P removal in grain) - 54.418; \(R^2 = 0.86\). These data show
that changes in soil P test levels may represent an appropriate method to estimate apparent crop-nutrient uptake. Greater change in soil P test levels in the 0 to 5 cm layer might indicate greater nutrient removal from that layer of the soil. Fernández et al. (2008) also showed greater change in nutrient test levels in the top 5 cm of the soil of a no-till soybean field and indicated that the change was related to crop uptake and not to environmental conditions that could have induced changes in the nutrient availability of the soil. We also observed reduction in P test levels at the soil surface of the NTDB and STDB treatments, along with a trend for increasing P test levels in the subsurface when 36 kg P ha$^{-1}$ yr$^{-1}$ was subsurface-banded (Figure 3.5). These data indicate that apparent P uptake is high in the surface layer even when P fertility is concentrated in a subsurface band. These data indicate roots effectively extract nutrients from the entire rooting depth, especially the soil surface, and nutrient uptake may not be influenced by the method of fertilizer application. This may be an important consideration when evaluating fertilizer use efficiency of various nutrient placement techniques.

Apparent P uptake was greater at the BR than the IR position in the surface 5 cm of the soil for all tillage/fertilizer placement treatments (Figure 3.6). The STDB system also showed significant decline in soil P test levels at BR at the 5 to 10 cm depth. It is possible that greater water availability within the top 10 cm of the soil at BR position in STDB compared to NTBC (Table 3.1, Figure 3.2), led to greater apparent nutrient uptake for STDB. The STDB system also showed significant declines in P test levels at IR and BR positions at depths below 10 cm (Figure 3.6). Greater declines in soil P test levels in the subsurface layers in STDB indicate that this system may be providing overall better soil conditions for nutrient uptake compared to the NTBC and NTDB systems. This advantage in apparent nutrient uptake in STDB may be
important in soybean production and translate into the observed higher seed yield compared to NTBC and NTDB.

Between the R1 and R3 development stages there was no statistical difference in soil P or K test levels, with only a numerical decline of 2.4 mg P kg\(^{-1}\) and 1.0 mg K kg\(^{-1}\). Since there were no treatment differences, soil test values followed similar patterns at both development stages, and the R1 development stage represents the start of rapid nutrient and dry matter accumulation of soybean (Ritchie et al., 1994), we elected to present only R1 data (Table 3.3, Figure 3.5 and 3.6). The lack of difference in soil P and K test levels over a short period of time (R1 to R3 development stage) is possibly related to a large buffer capacity of the soil. Also, as already mentioned, variability in soil K was large, and likely limited our ability to establish statistical differences for this nutrient between the two development stages. Compared to the unfertilized P plots, soil P test levels for the top 40 cm of the soil averaged 5 mg kg\(^{-1}\) more with annual applications of 36 kg P ha\(^{-1}\) (Table 3.3). Similarly, compared to the unfertilized plots, soil K test levels averaged 28 mg kg\(^{-1}\) more in the top 40 cm of the soil when K was applied at a rate of 168 kg K ha\(^{-1}\) yr\(^{-1}\). The greater P and K soil test levels was expected because these fertilizer application rates were designed to build up soil test levels by exceeding the nutrient removal rates in seed (Fernández and Hoeft, 2009). Over the three-year period of the study, subtracting the amount of actual nutrient removed in harvested seed of soybean and corn from the total P and K applied, we estimated that the 36 kg P ha\(^{-1}\) yr\(^{-1}\) rate provided 18 kg P ha\(^{-1}\) yr\(^{-1}\) to build up soil P test levels and the 168 kg K ha\(^{-1}\) yr\(^{-1}\) rate provided 128 kg K ha\(^{-1}\) yr\(^{-1}\) to build up soil K test levels (Fernández and Hoeft, 2009).

The unfertilized treatments showed significant vertical stratification with 2.0 times greater soil P test levels and 1.6 times greater soil K test levels in the top 5 cm of the soil than in
the 5 to 10 cm depth increment (Table 3.3). This also reflects starting nutrient distribution conditions at this site. Compared to the unfertilized plots, broadcast applications of 36 kg P ha\(^{-1}\) yr\(^{-1}\) and 168 kg K ha\(^{-1}\) yr\(^{-1}\) over a three-year period increased soil test levels in the surface 5 cm by 26 mg P kg\(^{-1}\) and 110 mg K kg\(^{-1}\), respectively. Since P and K are essentially immobile in this soil, the surface (0 to 5 cm) to subsurface (5 to 10 cm) concentration ratio increased by 86% for P and by 32% for K with broadcast applications compared to the unfertilized treatment (Table 3.3). While soil surface P test levels in the 36 kg P ha\(^{-1}\) yr\(^{-1}\) rate are not considered excessive for soybean production (Fernández and Hoeft, 2009), our study indicates that continuous broadcast applications of P over time have the potential to increase P test levels in the soil surface. High P test levels in the soil surface can represent an environmental hazard because of greater potential for environmental degradation in the event of soil P runoff from agricultural fields into bodies of water (McIsaac et al., 1995).

When fertilizer was applied in the subsurface band (in NTDB and STDB), the degree of vertical nutrient stratification for the 0 to 5 versus the 5 to 10 cm depth decreased by 65% compared to the same application in NTBC. Thus, subsurface P applications (where the soil disturbance for the application does not increase soil erosion potential) could help reduce some of the potential environmental concerns related to P fertilization of no-till. Compared with the unfertilized treatments, subsurface application increased test levels in the soil surface by 7 mg P kg\(^{-1}\) and 42 mg K kg\(^{-1}\). This is likely the result of greater P and K cycling with fertilization (Table 3.2) as the crop removes nutrients from the subsurface and deposits them on the soil surface in the form of crop residue. While these data are only for a limited number of years, they might indicate that cycling of nutrients from the subsurface to the surface may be important to minimize continuous depletion of fertility test levels at the soil surface in systems where P and K
are being repeatedly applied at the subsurface. These data may further indicate that subsurface banding may be an alternative way to supply P in conservation tillage systems without substantially increasing P test levels in the soil surface.

Subsurface banding of fertilizers—even over a short period of three years—caused substantial increase in P and K test levels in the location of the band (Table 3.3). These results agree with others that have observed the development of localized high fertility with fertilizer banding in conservation tillage systems (Mallarino and Borges, 2006; Rehm, 1995). Although subsurface banding may produce some of the above-mentioned benefits in reducing soil surface P levels for environmental protection, Mallarino and Borges (2006) noted that it is difficult to determine how to best soil sample to accurately predict the nutrient status of a field with such localized fertility. Not only the sampling location with respect to the fertilizer band may be important, but also the depth of sampling needs to ensure the concentrated band is being taken into account in the overall estimate of fertility. While it is generally agreed that increasing the number of cores per sample can increase the accuracy in the prediction of fertility through soil testing, to-date there is no universal agreement on how to collect soil samples when fields in conservation tillage systems receive sub-surface band fertilization (Rehm et al., 2001). At the 5 to 10 cm depth, STDB increased K test levels at the IR- compared to the BR-position, and a similar trend occurred for P. While it is not clear what caused this increase, we suspect it could have been the result of a combination of slight subsidence of the soil surface (that caused us to capture part of the band in the 5 to 10 cm depth) and greater-than-expected variability in the application depth. This finding further highlights some of the potential difficulties associated with taking a soil sample that accurately predicts the fertility of a field with highly localized fertility.
CONCLUSIONS

Application of P and K in the STDB and NTDB treatments resulted in less of these nutrients on the soil surface relative to broadcast applications in NTBC. Subsurface banding may be a desirable option for P fertilization in conservation tillage systems where high P in the soil surface represents a potential for environmental degradation in the event of P runoff. While subsurface banding of P and K created zones of localized fertility in the application zone, there was no evidence of root proliferation in response to this localized fertility. Roots typically proliferate in response to P when the soil volume is P-limited (Hallmark and Barber, 1984). In our study, the lack of root proliferation in response to localized P was likely the result of adequate P levels within the top 18 cm of the soil. Greatest soybean root densities occurred in the top 5 cm of the soil, markedly decreasing with increasing soil depth regardless of tillage/fertilizer placement treatment. This indicates that under the conditions of this study, banding fertilizer may not improve nutrient availability as a result of promoting root proliferation. Across all tillage/fertilizer placement treatments, apparent nutrient uptake was greatest in the top 5 cm of the soil at the BR position. This was also the zone of greater soil water content in STDB relative to NTBC and NTDB. In the top 5 cm of the soil at the BR position soybean plants in NTBC produced and maintained a larger root system than STDB. Even though NTBC produced a larger root system, accumulations of P and K in above-ground plant tissues as well as apparent nutrient uptake rate per unit of root surface area were greater for STDB than NTBC. This indicates that a larger root system in NTBC was not sufficient to increase nutrient accumulation compared to STDB. Competitive advantage for soybean production with STDB relative to the no-till systems (NTBC and NTDB) arises from improved conditions for nutrient uptake, including greater soil
water content within the top 10 cm of the soil at the BR position where the greatest apparent nutrient uptake occurred.

ACKNOWLEDGMENTS

Partial funding for this project was graciously provided by the Illinois Fertilizer Research and Education Council. We extend our appreciation to Kristin Greer and William Decker for their assistance with field and laboratory procedures.
REFERENCES


Table 3.1. Three-year mean volumetric soil water content ($\Theta_v$) at seed-filling (R5-R6) development stage as affected by soil depth, tillage/fertilizer placement treatment [no-till broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)] and crop-row position (IR, in-row; BR, between-rows).

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Tillage/fertilizer placement</th>
<th>IR $\Theta_v$ cm$^3$ cm$^{-3}$</th>
<th>BR $\Theta_v$ cm$^3$ cm$^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>NTBC</td>
<td>0.19 a</td>
<td>0.19 b</td>
</tr>
<tr>
<td></td>
<td>NTDP</td>
<td>0.19 a</td>
<td>0.19 b</td>
</tr>
<tr>
<td></td>
<td>STDP</td>
<td>0.20 a</td>
<td>0.23 a*</td>
</tr>
<tr>
<td>5-10</td>
<td>NTBC</td>
<td>0.22 b</td>
<td>0.22 b</td>
</tr>
<tr>
<td></td>
<td>NTDP</td>
<td>0.23 a</td>
<td>0.22 b</td>
</tr>
<tr>
<td></td>
<td>STDP</td>
<td>0.21 b</td>
<td>0.26 a*</td>
</tr>
<tr>
<td>10-15</td>
<td>NTBC</td>
<td>0.26 a*</td>
<td>0.23 b</td>
</tr>
<tr>
<td></td>
<td>NTDP</td>
<td>0.26 a</td>
<td>0.25 a</td>
</tr>
<tr>
<td></td>
<td>STDP</td>
<td>0.23 b</td>
<td>0.22 c</td>
</tr>
<tr>
<td>15-20</td>
<td>NTBC</td>
<td>0.27 a</td>
<td>0.26 a</td>
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<td></td>
<td>NTDP</td>
<td>0.26 a*</td>
<td>0.22 c</td>
</tr>
<tr>
<td></td>
<td>STDP</td>
<td>0.26 a*</td>
<td>0.25 b</td>
</tr>
<tr>
<td>20-40</td>
<td>NTBC</td>
<td>0.26 ab*</td>
<td>0.23 a</td>
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<tr>
<td></td>
<td>STDP</td>
<td>0.27 a*</td>
<td>0.23 a</td>
</tr>
</tbody>
</table>

† Within column and depth means followed by the same lowercase letter are not significantly different.
* Indicate significant difference between means within row.
Table 3.2. Three-year mean root surface area density (RSD), phosphorus (P) and potassium (K) accumulation in above-ground vegetative tissue, and estimated P and K uptake rate per unit of root surface area on the top 40 cm of soil depth at stage R1 as affected by tillage/fertilizer placement [no-till/broadcast (NTBC), no-till/deep band (NTDB) and strip-till/deep band (STDB)], P rate (0 and 36 kg K ha\(^{-1}\) yr\(^{-1}\)), and K rate (0 and 168 kg K ha\(^{-1}\) yr\(^{-1}\)).

<table>
<thead>
<tr>
<th>Tillage /fertilizer Placement</th>
<th>RSD P rate</th>
<th>RSD K rate</th>
<th>Accumulation P rate</th>
<th>Accumulation K rate</th>
<th>Uptake rate(^{†}) P rate</th>
<th>Uptake rate(^{†}) K rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>36</td>
<td>168</td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td>cm(^2) cm(^{-3})</td>
<td>kg P ha(^{-1})</td>
<td>kg K ha(^{-1})</td>
<td>mg P m(^2) d(^{-1})</td>
<td>mg K m(^2) d(^{-1})</td>
<td></td>
</tr>
<tr>
<td>NTBC</td>
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<td>0.41</td>
<td>0.46(^{†})</td>
<td>0.43</td>
<td>2.9</td>
<td>3.2</td>
</tr>
<tr>
<td>NTDB</td>
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<td>0.39</td>
<td>0.40(^{ab})</td>
<td>0.39</td>
<td>3.3</td>
<td>3.9</td>
</tr>
<tr>
<td>STDB</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37(^{b})</td>
<td>0.38</td>
<td>3.6</td>
<td>4.0</td>
</tr>
<tr>
<td>Mean</td>
<td>0.40</td>
<td>0.39</td>
<td>0.41</td>
<td></td>
<td>3.3(^{B})</td>
<td>3.7(^{A})</td>
</tr>
</tbody>
</table>

Data are back-transformed means from natural log-transformed data.

\(^{†}\) Uptake rate was calculated as the mean K accumulation per day from emergence (VE) to R1 development stage divided by the root surface area density at R1.

\(^{‡}\) Means within column followed by the same lowercase letter are not significantly different.

\(^{§}\) Means within row and measurement variable followed by the same uppercase letter are not significantly different.
Table 3.3. Three-year mean soil P and K test levels at growth stage R1 for low and high P (0 and 36 kg P ha\(^{-1}\) yr\(^{-1}\)) and K (0 and 168 kg K ha\(^{-1}\) yr\(^{-1}\)) fertilizer rates and tillage/fertilizer placement treatment [no-till/broadcast (NTBC); no-till/deep band (NTDB); and strip-till/deep band (STDB)], crop-row position (IR = in-row; BR = between-rows), and soil depth.

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>NTBC IR</th>
<th>NTBC BR</th>
<th>NTDB IR</th>
<th>NTDB BR</th>
<th>STDB IR</th>
<th>STDB BR</th>
<th>NTBC IR</th>
<th>NTBC BR</th>
<th>NTDB IR</th>
<th>NTDB BR</th>
<th>STDB IR</th>
<th>STDB BR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 kg P ha(^{-1}) yr(^{-1})</td>
<td>36 kg P ha(^{-1}) yr(^{-1})</td>
<td>mg P kg(^{-1})</td>
<td>mg K kg(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>23a</td>
<td>23a</td>
<td>24a</td>
<td>22a</td>
<td>29a</td>
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<td>28a</td>
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<td>13b</td>
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<td>6c</td>
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<td>18</td>
<td>12</td>
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<td>17</td>
</tr>
<tr>
<td></td>
<td>0 kg K ha(^{-1}) yr(^{-1})</td>
<td>168 kg K ha(^{-1}) yr(^{-1})</td>
<td>mg K kg(^{-1})</td>
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<td>123bc</td>
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<td>179b</td>
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<td>240a*</td>
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<td>112c</td>
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<td>104c</td>
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<td>116b</td>
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<td>132b</td>
</tr>
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<td>131b</td>
<td>123bc</td>
<td>138b</td>
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<td>143b</td>
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<td>141b</td>
</tr>
<tr>
<td>0-40</td>
<td>128</td>
<td>127</td>
<td>131</td>
<td>132</td>
<td>136</td>
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<td>150</td>
<td>154</td>
<td>180</td>
<td>146</td>
<td>193</td>
<td>158</td>
</tr>
</tbody>
</table>

Data are back-transformed means from natural log-transformed data.
† Within column and fertility level, means followed by the same lowercase letter are not significantly different.
* Indicate significant difference between means within row and tillage/fertilizer placement treatment for each fertilizer rate.
FIGURES

Figure 3.1. Volumetric soil water content ($\Theta_v$) for the top 40 cm of the soil for the 36-168 kg P-K ha$^{-1}$ yr$^{-1}$ rate for different crop-row positions (IR, in-row; BR, between-rows), and precipitation, 2007 to 2009. Soybean developmental stages include emergence (VE) to full seed (R6).
Figure 3.2. Three-year mean volumetric soil water content (\(\Theta_v\)) for various depths and weighed average for the top 40 cm of soil during soybean reproductive stages [including beginning flower (R1) to full seed (R6)] for the 36-168 kg P-K ha\(^{-1}\) yr\(^{-1}\) rate as affected by crop-row positions (in-row and between-rows), and tillage/fertilizer placement treatment [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)].
Figure 3.3. Root length density with soil depth as affected by development stage (R1 and R3), crop-row position (IR, in-row; BR, between-rows), and tillage/fertilizer placement treatment [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)]. Same lowercase letters indicate no significant difference between tillage/fertilizer placement treatments for a given depth. Same uppercase letters indicate no significant difference between soil depths, averaged over tillage/fertilizer placement treatment.
Figure 3.4. Three-year mean root diameter averaged across R1 and R3 development stage at different soil depths as impacted by crop-row position (IR, in-row; BR, between-rows), and tillage/fertilizer placement treatment [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)]. Same lowercase letters indicate no significant difference between tillage/fertilizer placement treatments for a given depth within crop-row position. Same uppercase letters indicate no significant difference between soil depths within crop-row position.
Figure 3.5. Changes in mid-season (stage R1) soil P test levels between 2007 and 2009 for 0 and 36 kg P ha$^{-1}$ yr$^{-1}$ fertilizer rate for different soil depths averaged across crop-row position (IR, in-row; BR, between-rows) for the different tillage/fertilizer placement treatments [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)]. * indicate significantly different from zero (no change) ($P \leq 0.1$). Data are back-transformed means from natural log-transformed data.
Figure 3.6. Change in soil P test levels between 2007 and 2009 at R1 development stage for 0 kg P ha\(^{-1}\) yr\(^{-1}\) fertilizer rate for different soil depths and crop-row position (in-row and between-rows) for the different tillage/fertilizer placement treatments [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)]. * indicate significantly different from zero (no change) for the specified crop-row position. Data are back-transformed means from natural log-transformed data.
CHAPTER 4

GROWTH, PHOSPHORUS AND POTASSIUM ACCUMULATION, AND SOYBEAN SEED COMPOSITION WITH BROADCAST AND BAND-APPLIED FERTILIZER IN NO-TILL AND STRIP-TILL

(Under preparation to be submitted to Agron. J.)

ABSTRACT

There has been increasing interest in strip-till treatments as a conservation method that avoids crop residue management challenges associated with no-till treatments. Strip-till is also advantageous in that it provides an easy alternative for deep banding of fertilizers. The objective of this study is to evaluate the influence of phosphorus (P) and potassium (K) rate and placement in no-till and strip-till treatments on soybean \( [Glycine \text{ max} \ (L.) \ Merr.] \) above-ground growth, nutrient accumulation, and seed composition. A three-year field experiment was conducted near Urbana, Illinois on Flanagan silt loam and Drummer silty clay loam soils with tillage and fertilizer placement as the main (whole) plots: no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB) with deep placement of fertilizers at 15 cm. The split-plot and split-split plot consisted of four P (0, 12, 24, and 36 kg P ha\(^{-1}\) yr\(^{-1}\)) and four K (0, 42, 84, and 168 kg K ha\(^{-1}\) yr\(^{-1}\)) rates. Generally, greater dry matter accumulation, canopy height, and leaf area index (LAI) were found for STDB than for NTBC. Since protein and oil concentrations were unaffected, these differences in shoot parameters translated into significantly greater seed yield with STDB than NTDB and NTBC, consequently greater protein and oil yield. The greater biomass accumulation with STDB resulted in greater P accumulation than with the NTBC treatments. Throughout the growing season P and K concentration and accumulation in leaf tissue increased with P and K fertilization rate, respectively, but fertilizer placement had no
effect on leaf tissue composition. Soybean production with strip-till resulted in a relative increase of protein and oil yield by enhancing reproductive phase plant growth and P accumulation. 

Abbreviations: NTBC, no-till/broadcast; NTDB, no-till/deep band; STDB, strip-till/deep band.

INTRODUCTION

Soybean is typically planted in rotation with corn (Zea mays L.); and second to corn, is the most widely grown crop in the Midwestern U.S. with approximately 26.8 million hectares planted in 2010 (USDA/NASS 2010). In 2008, in the U.S., 62% of full-season, and 76% of double-cropped (planted after wheat harvest), soybeans were planted under no-till or other conservation tillage systems (CTIC 2008). While no-till is considered superior to other tillage systems for soil conservation (Rhoton, 2000) and economic efficiency compared to conventional tillage (Smart, 1999), no-till can pose unique challenges for crop production. For example, compared to conventional tillage, no-till generally results in wetter and cooler soils early in the growing season because crop residue cover has reflective and insulative properties that minimize evaporation rates and, heat flux from the sun to penetrate in the soil. These wetter and cooler conditions retard soybean growth reduce P and K availability (Barber, 1971; Fortin, 1993), and decrease seed yield (Philbrook et al., 1991; West et al., 1996; Yin and Al-Kaisi, 2004). Since wet and cool conditions often occur early in the season and soybeans are generally planted following corn, these conditions are of greater concern for corn than soybean. However, in recent years, several reports have indicated a substantial yield increase of up to 9% with early-planted soybeans (late April) compared to late May planting (De Bruin and Pedersen, 2008). With early planting, it is possible that the drawbacks observed for no-till corn could become more important for soybean.
Given limitations of no-till for crop production, strip-till has been proposed as an option that combines the improved seedbed conditions of conventional tillage with the conservation benefits of no-till (Jones et al., 1994; Morrison, 2002). The narrow tilled, residue free planting row created with strip-till can increase early season soil temperature and aeration and reduce excess soil water in the seedbed similar to conventionally-tilled soil. On the other hand, the undisturbed residue left on the soil surface outside the strip-tilled zone protects soil from water and wind erosion and helps conserve soil moisture similar to no-till treatments (Hares and Novak, 1992). The enhanced seedbed conditions in strip-till have been reported to improve early planting, uniform emergence, and ultimately seed yield compared to no-till for soybean (Bolton and Booster, 1981; Kaspar et al., 1990; Vyn and Raimbault, 1992; Opoku et al., 1997; Vyn et al., 1998; Licht and Al-Kaisy, 2005; Perez-Bidegain et al., 2007) as well as corn (Vetsch and Randall, 2002; Vyn and Raimbault, 1992). Farmaha et al (2011a) reported, even without early planting, an increase in soybean yield with strip-till compared to no-till and attributed the benefit of the farmer with improved soil conditions and greater seasoned soil water content.

Strip-till also allows simultaneous subsurface application of fertilizer during tillage operation. Subsurface applications of P and K may be preferred over broadcast applications in certain situations. The long-term consequence of broadcast P and K fertilizer applications in no-till often results in vertical stratification of these nutrients with greater concentrations at the soil surface (Fernández et al., 2008; Houx et al., 2011). This stratification may reduce nutrient availability and nutrient accumulation in soybean shoots when the nutrient-rich surface dries out, while subsurface applications can have the opposite effect (Eckert and Johnson, 1985; Ebelhar and Varsa, 2000). Hairston et al. (1990) reported that deep placement of K produced significantly greater no-till soybean seed yield than broadcast surface applications. Similarly,
applying P and K at 15 to 20 cm depth in ridge-till increased the uptake of both nutrients for soybean as early as the V5-V6 development stage compared to broadcast treatments (Borges and Mallarino, 2003). On the other hand, several studies have observed no additional increase in seed yield over broadcast applications with subsurface banding (Borges and Mallarino, 2000; Yin and Vyn, 2002; Rehm and Lamb, 2004). However, since sub-surface banding does not reduce seed yields relative to broadcast applications, subsurface banding may still be beneficial for environmental considerations. Vertical stratification with greater P concentrations at the soil surface in no-till can increase the chance of P runoff from fields into bodies of water (McIsaac et al., 1995). Deep banding of P can effectively reduce surface P test levels (Farmaha et al., 2011b) and reduce the potential environmental degradation caused by P runoff (Randall and Vetsch, 2008).

The limited amount of information on the effect of strip-till on soybean seed yield and the inconsistency in results from nutrient placement studies suggests the need for further investigation to identify interactions between crop development, tillage and, fertilizer placement on crop production and seed parameters. Such information can potentially help reconcile agronomic results from previous studies. In season growth analysis has long being recognized as a way to quantify crop response relative to environment factors (Radford, 1967; Hunt, 1982). Yusuf et al. (1999) observed that compensatory growth can help early season, slow-growing no-till soybeans attain similar yields to conventionally-tilled soybeans. Soybean plants take up about 75% of total P and K during pod development (starting at R3) which continues through the middle to the latter part of the growing season (Hanway and Weber, 1971).

Fernández et al. (2009) found that having adequate K supply early in development was important to improve soybean growth and seed yield. Similarly, a few studies with deep
placement of P and K have reported increased soybean growth and nutrient uptake during vegetative development stages compared to broadcast applications (Borges and Mallarino, 2000; Borges and Mallarino, 2003), but other studies have shown no such differences due to nutrient placement (Ebelhar and Varsa, 2000; Farmaha et al., 2011a). Finally, not many studies have been designed to evaluate the effect of tillage and nutrient placement on seed quality parameters such as oil and protein. Although soybean protein and oil concentrations are largely affected by genetic factors and environmental conditions during the seed-filling period, management practices can also have a significant impact (Wilcox, 1985; Brummer et al., 1997; Temperly and Borges, 2006). Yin and Vyn (2003) observed that compared to surface broadcast, 10 cm deep placement of K increased plant K uptake, seed K concentration, and oil concentration of soybean in low-K testing soils. Others have observed K deficiency reduces protein concentration (Koch and Mengel, 1977) and oil concentration (Sale and Campbell, 1986) likely due to a decrease in photosynthesis and phloem translocation (Wallingford, 1980).

Previous work (Farmaha et al., 2011a, b) examined the response of strip-till, no-till and P and K placement on belowground parameters such as root development, soil water, and soil nutrient distribution and how those parameters influenced seed yield and seed nutrient concentration. The objectives of this study are to evaluate the effect of strip-till, no-till and P and K placement on aboveground growth parameters, plant nutrient accumulation, seed oil and protein concentration and accumulation.

**MATERIALS AND METHODS**

**Site Description**

Soybeans were grown for three years (2007–09) in rotation with corn at the Crop Sciences Research & Education Center near Urbana, Illinois on Flanagan silt loam (Fine, smectitic, mesic Aquic Argiudolls) and small sections with Drummer silty clay loam soils (Fine-
silty, mixed, superactive, mesic Typic Endoaquolls). These soils are classified as poorly drained and somewhat poorly drained but subsurface tiles to improve drainage. Pre-treatment soil test values in the top 18 cm of soil were: Bray P$_1$ (Bray and Kurtz, 1945) 20 mg kg$^{-1}$ and 1 M NH$_4$OAc extractable K (Warncke and Brown, 1998) 167 mg kg$^{-1}$.

The study was conducted in a randomized complete-block design with a split-split-plot arrangement and three replications. The main (whole) plot included three tillage/fertilizer placement treatments: no-till/broadcast (NTBC); no-till/deep band (NTDB); and strip-till/deep band (STDB). The split-plot treatments were four P application rates (0, 12, 24, and 36 kg P ha$^{-1}$ yr$^{-1}$), and the split-split plot treatments were four K application rates (0, 42, 84, and 168 kg K ha$^{-1}$ yr$^{-1}$). For the unfertilized plots (0 kg P ha$^{-1}$ yr$^{-1}$ and 0 kg K ha$^{-1}$ yr$^{-1}$) each tillage/fertilizer placement treatment received the corresponding soil disturbance created by the application equipment. Plots dimensions were 6 m wide x 23 m long with 76 cm row spacing. Broadcast fertilizer treatments were supplied using a hand held spin-spreader. Band application of fertilizers was at 15 cm depth directly underneath the planting row using a Gandy Orbit Air applicator (Model 6212C, Gandy, Owatonna, MN). The NTDB treatments were applied using 2-cm-wide, low-disturbance, NH$_3$ thin profile knives (minimum tillage knife Model 003-0000018, Fertilizer Dealer Supply, Philo, IL). For the STDB treatment, application was made with a wavy cutting coulter and row cleaners (residue managers) in front of modified NH$_3$ knives (original mole knife – Model 003-0100411, Fertilizer Dealer Supply) with closing discs (berm shapers) behind the mole knife. The cultivar Hi-Soy2846 (maturity group 2.8) was planted on 25 May 2007 and 13 June 2008 and cultivar Pioneer 93M42 (maturity group 3.4) was planted on 24 June 2009 at a seeding rate of 376,000 seeds ha$^{-1}$, 5 cm deep in the soil. The complete description of
the experimental details, crop management practices, and initial soil chemical characteristics are presented by Farmaha et al. (2011a).

**Sample Collection and Analysis**

In 2008 and 2009, vegetative samples were collected from 0.5 m² (0.66 x 0.76 m²). Sampling started at V1 development stage and continued at 9-day intervals through R6 for a total of eight sampling times. Development stages were determined as described by Fehr and Caviness (1977). In 2008 samples were collected at V1, V2, V4, R1, R2, R4, R5, and R6 development stages and V1, V2, R1, R2, R4, R5, R5, and R6 in 2009. While the eight sampling events occurred during slightly different development stages in the two years, the seasonal patterns were similar across years. Compared to 2008, in 2009 plants developed faster due to later planting and flowering (R1) began at the V4/V5 vegetative growth stage. Thus, while some of the development stages for a particular sampling time were different across years, in terms of growth the sampling periods were similar, thus and data were grouped across years by sequential sampling event. For the first four samplings, samples were collected from every treatment and replication; thereafter sampled were only collected from plots receiving factorial fertility combinations of 0 and 36 kg P ha⁻¹ yr⁻¹ and 0 and 168 kg K ha⁻¹ yr⁻¹, representing extreme low and high rates.

Plant height was measured from the soil surface to the uppermost trifoliate. Plants were cut at the soil surface and partitioned into leaves, stems, and petioles to determine leaf area using LI-COR 3100 leaf area meter (LI-COR, Lincoln, NE) and dry biomass by oven drying 60° C for 72 hours to achieve constant weight. Dry stem, pods, petioles, and leaf samples were combined, ground to pass a 1-mm mesh screen on a Wiley mill (Standard Model 3; Arthur H. Thomas Co., Philadelphia, PA), and chemically analyzed by A&L Great Lakes Laboratories, Inc. (Fort
Wayne, IN) following the official methods of analysis of AOAC International (Horwutz, 2000). Nutrient accumulation was calculated by multiplying dry matter accumulation by nutrient concentration. Crop growth rate (CGR), leaf area index (LAI), leaf area ratio (LAR), net assimilation rate (NAR), relative growth rate (RGR), and specific leaf weight (SLW) were calculated using equations given in Fernández et al. (2009). ECH2O EC-5 and EC-20 moisture probes and Em-50 digital data loggers (Decagon Devices Inc., Pullman, WA) were installed at 0-5, 5-10, 10-15, 15-20, and 20-40 cm soil depth increments at IR and BR positions for continuous recording of soil water content throughout the growing season. Measurements were taken from three tillage/fertilizer placement treatments received only 36-168 kg P-K ha⁻¹ yr⁻¹ rate.

At the end of each of the three seasons, harvested seed samples were collected to measure protein and oil concentrations using near-infrared reflectance spectroscopy (Infratec Model 1229 Grain Analyzer, Foss Tecator Hoganas, Sweden).

**Statistical Analysis**

Data were analyzed using MIXED procedure of SAS (SAS Institute, 2009). Years, blocks and their interactions with treatments were considered random effects. The normality assumption of the residuals was tested using Shapiro-Wilk test in the UNIVARIATE procedure of (SAS Institute, 2009). The homogeneity of variances assumption was tested visually from the residual plots (plot the residuals versus fitted values). Mean comparisons among treatments were done using Tukey’s studentized range honestly significant difference (HSD) test to control experiment-wise error and with the Tukey-Kramer test for unbalanced data. The REG and CORR procedure of SAS (SAS Institute, 2009) were used to develop linear regression equations and estimate the Pearson correlation coefficient (r) between variables, respectively. Single degree of
freedom contrasts were constructed between years to test relative effects on seed protein and oil. Treatment effects were declared significant at an alpha level of 0.1.

RESULTS AND DISCUSSION

Seed Protein, Oil Concentration, and Yield

Soybean seed protein and oil yields were significantly affected by tillage/fertilizer placement treatment (Table 4.1). Protein and oil yield associated with STDB were both, 8% greater relative to the no-till treatments (NTBC and NTDB) (Table 4.2). Since protein and oil concentrations were not affected by tillage/fertilizer placement, the increase in both protein and oil yield was in direct proportion to the 8.5% relative increased in seed yield with STDB compared to the no-till treatments (Farmaha et al., 2011a).

Phosphorus fertilization rates of 24 and 36 kg P ha$^{-1}$ yr$^{-1}$ increased seed protein and oil yield compared to lower P fertilization rates (Table 4.2). While seed protein and oil concentrations were affected by P fertilization rate, such differences were not meaningful. As with tillage/fertilizer placement treatment, the increase in seed protein and oil yield with increased P rate was a direct result of increased seed yield as reported elsewhere (Farmaha et al., 2011). A significant tillage/fertilizer placement by P fertilization rate interaction (Table 4.1) was explained by 10% greater protein yield with STDB as compared to the no-till treatments at the 0 kg P ha$^{-1}$ yr$^{-1}$ rate (Figure 4.1). Also, it is worth noting that while protein yield increased with increasing P rate for NTBC and NTDB, yields were lower than STDB even at the highest P rate.

Soil water content can have a profound impact on P availability and crop growth, especially for low P test soils (Barber, 1995). Previously we reported greater soil water content in the STDB treatment than the no-till treatments (Farmaha et al., 2011b). It is possible that
increased seed protein yield for STDB at the 0 kg P ha\(^{-1}\) yr\(^{-1}\) fertilizer rate compared to no-till treatments is a reflection of greater P availability resulting from greater soil water content.

Potassium fertilization rate had a significant impact on seed protein and oil concentration and yield (Table 4.1). There was an inverse relationship in which protein concentration decreased while oil concentration increased with increasing K fertilizer rate (Table 4.2). Overall, for each 2.8 g kg\(^{-1}\) decrease in protein concentration there was 1 g kg\(^{-1}\) increase in oil concentration. Similar inverse relationships have been reported by others (Gaydou and Arrivets, 1983; Sale and Campbell, 1986; Yin and Vyn, 2003). It was previously shown for this study that increasing K fertilizer rate increased seed K concentration (Farmaha et al. 2011a). Several researchers have studied the relation between K fertilization, seed K content, and seed quality traits (such as protein and oil content) (Sale and Campbell, 1986; Vyn et al., 2002; Yin and Vyn, 2003). As observed here, these authors also observed a positive relationship between seed K concentration and oil concentration. However, the oil concentration response to K fertilizer rate was not greater than the seed yield response to K fertilizer rate previously reported (Farmaha et al., 2011a). Thus, these results would indicate that for soybean there is not a K management strategy to increase oil production that is independent of a management strategy to increase seed yield.

Seed yield was well correlated with protein and oil yield (Figure 4.2a and b, respectively) as expected since protein and oil yield responded to treatments in a similar manner as seed yield. Conversely, protein and oil concentrations were not correlated to seed yield. Similar results were observed by Temperly and Borges (2006). Oil and protein measurements in 2007 and 2008 were similar but differed considerably from that in 2009 (Table 4.1). Correlation of protein yield with seed yield showed that 2009 generally produced lower seed and protein yields than 2007 and
2008. However, the slopes and intercepts for each year were not significantly different, thus the correlation was calculated across years (Figure 4.2a). Correlation of oil yield with seed yield also showed overall lower seed and oil yield for 2009 than 2007 and 2008 (Figure 4.2b), but unlike protein, the slope of the correlation for oil yield in 2007 and 2008 were similar to each other but significantly different than 2009. The reason for this difference is that late planting in 2009 not only reduced seed yield, but also lowered oil concentration. Oil concentration was 176 g kg\(^{-1}\) in 2009 compared to 200 g kg\(^{-1}\) for both 2007 and 2008. On the other hand protein concentration in 2009 was 336 g kg\(^{-1}\), significantly greater than the 327 g kg\(^{-1}\) observed in 2007 and 317 g kg\(^{-1}\) in 2008 which helped integrate the 2009 data. Perhaps most importantly, these results indicate that management objectives to increase seed yield may not be different than management objectives to increase protein and oil production.

**Dry Matter Accumulation**

Dry matter accumulation measured across the growing season was consistently higher for STDB than NTBC starting at V2 through the R5 development stage. These differences were only significant starting at R1/R2 (Figure 4.3). The NTDB treatment showed in general an intermediate response between NTBC and STDB, but at R2/R4 and R5 stages dry matter accumulation in NTDB was similar to NTBC and significantly lower than for STDB. Often strip-till is considered a superior system relative to no-till for early planted soybeans because the strip allows the soil to dry and warm up to a greater extent and improve germination and crop establishment (Perez-Bidegain et al., 2007). This study, without early planting, indicates that some of the benefits of strip-till for crop establishment during the initial development stages are not limited to early-planted soybeans. Previously, Farmaha et al. (2011b) showed that the greater soil water content and increased nutrient uptake in the STDB treatment provided better
conditions for crop production compared to the no-till treatments. The weekly average soil water content prior to each plant sampling shows the effect of STDB on soil water availability was more pronounced for the top 10 cm and BR position as compared to the IR position (Figure 4.4). At IR, NTBC treatments had higher soil water content than the other two treatments. This could be due to the spatial pattern of prior crop residue distribution. In contrast, STDB had a freshly tilled row at the start which probably helped to conserve more soil water than other treatments reflecting its greater availability at BR position. We suspect better soil conditions for planting planting and greater soil water availability enabled increased soybean growth during the reproductive stage compared to the other two treatments. The improved conditions with STDB likely increased photo assimilate production and the observed greater dry matter accumulation compared to the no-till treatments. During the seed-filling period (R5 to R6), the rate of dry matter accumulation for the STDB treatment was reduced while remaining nearly constant for NTBC and NTDB, likely indicating that soybeans achieved maximum dry matter accumulation and maturity earlier in STDB than in the no-till treatments.

Application of 12 kg P ha⁻¹ yr⁻¹ increased dry biomass at V1 development stage by 16% relative to the 0 kg P ha⁻¹ yr⁻¹ rate (68 kg P ha⁻¹ for the check plot). Averaged across the first four sampling times (V1 to R1/R2), the 12 kg P ha⁻¹ yr⁻¹ rate increased dry matter accumulation by 8% compared to the check, but no further increases with additional P fertilization rates were observed. Average soil P test levels for the top 18 cm of the soil in the check plots was 15 mg P kg⁻¹ in fall 2008 and 14 mg P kg⁻¹ in fall 2009, which is considered limiting for soybean production (Fernández and Hoeft, 2009). These data illustrate the importance of adequate P fertility especially during the early development stages when a small developing root system is less able to exploit a large volume of the soil to acquire P. On the other hand, K fertilizer rate had
no effects on dry matter accumulation (data not shown). This lack of response was anticipated, since soil test levels for top 18 cm at the 0 kg K ha\(^{-1}\) yr\(^{-1}\) rate, averaged across samples collected in fall 2008 and 2009, were 150 and 154 mg K kg\(^{-1}\), respectively, which is considered sufficient to maximize soybean production (Fernández and Hoeft, 2009). These results in biomass production in response to P and K fertilizer rate support earlier findings showing soybean seed yield increase with P fertilization but not with K fertilization (Farmaha et al., 2011a). The point to register here is that these data illustrate the need of adequate P fertility even at early development stages, when soybean nutrient requirements are low, to establish the crop and possibly give it a competitive advantage that translates to greater seed yield at harvest. These results also agree with those of Fernández et al. (2009) who indicated that adequate soil fertility was critical for early growth of soybeans and to improve seed yield.

**Canopy Height**

Canopy height was found highest at R5 for all tillage/fertilizer placement treatments (Figure 4.5). The season average canopy height with STDB was 10% greater than the NTBC treatment, though differences were only significant at V4/R1 and at R5. The NTDB treatments produced intermediate values. As with dry matter accumulation, the consistently taller plants across most of the growing season for the STDB treatment compared to NTBC is likely the result of greater soil water content and better conditions for nutrient uptake, as reported by Farmaha et al. (2011b). Increased soybean canopy height for the strip-till relative to no-till has been observed by others (Oplinger and Philbrook, 1992). To our knowledge there are no reports showing soybean canopy height response to strip-till, but similar to our study Vyn and Raimbault (1992) observed strip-till corn produced taller plants and also greater grain yields than no-till. Increasing soybean plant height has long been recognized as a desirable trait to increase
seed yield (Walker and Cooper, 1982). In our study, averaged across fertilizer rate treatments, at R1/R2 development stage correlation of plant height to seed yield was high [Seed yield = 1.0 + 0.03 * (plant height); $R^2 = 0.53, P = 0.02$]. The $R^2$ values later in development were also high, ranging between 0.56 and 0.68 during the last four sampling times (R2/R4 to R6 development stages) (Data not shown). Similar results were observed for the correlation of plant height and seed oil and protein concentration.

Unlike dry matter accumulation that was influenced by P fertilization starting early in development, canopy height increased in response to P rate during soybean reproductive stages (Data not shown). Averaged across the last four samplings (R2/R4 to R6) the 36 kg P ha$^{-1}$ yr$^{-1}$ rate produced plants 88 cm tall, which represented a significant 3% increase relative to the 0 kg P ha$^{-1}$ yr$^{-1}$ rate. No differences in canopy height were observed in response to K rate.

**Plant Nutrient Analysis**

Tissue P concentration was not affected by tillage/fertilizer placement, thus treatment differences for P accumulation resemble the response observed for dry matter accumulation presented in Figure 4.3. Above-ground P accumulation was significantly greater with STDB than NTBC during the reproductive stages between R1/R2 and R5. At R5, soybeans in STDB had accumulated 14 kg P ha$^{-1}$, which represents an 18% increase in P accumulation over NTBC and a 10% increase in P accumulation over NTDB. It follows that, as mentioned earlier for dry matter accumulation, better soil conditions (including greater soil water content) in STDB reported by Farmaha et al. (2011b) increase the capacity of soybean for P uptake and biomass accumulation during the reproductive stages of development. Tissue K concentration and accumulation were not impacted by tillage/fertilizer placement treatments (data not shown).
Above-ground tissue P and K concentrations were maximized very early in development by the V2 stage (Table 4.3 and 4.4). As the crop increased in size, P and K concentrations became diluted within the plant while total nutrient accumulation continued to increase through the growing season (Table 4.3 and 4.4). These findings agree with previous work (Hanway and Weber, 1971). For nearly all development stages sampled, tissue P and K concentration and accumulation increased by increasing P and K fertilization rate, respectively. However, averaged across the growing season comparisons between the unfertilized treatments and the highest P and K fertilizer rates showed that the relative increase in both concentration and accumulation was approximately two times larger for K than for P. Averaged across all samplings, plant P increased 12% in concentration and 13% in accumulation with the 36 kg P ha\(^{-1}\) yr\(^{-1}\) rate over the 0 kg P ha\(^{-1}\) yr\(^{-1}\) check. Conversely, averaged across all samplings, plant K increased 25% in concentration and 24% in accumulation with the 168 kg K ha\(^{-1}\) yr\(^{-1}\) rate over the 0 kg K ha\(^{-1}\) yr\(^{-1}\) check. Our results are in accordance with Borges and Mallarino (2000) who reported increased P uptake with P fertilization in long-term trials conducted on medium P testing soils. Rate of P fertilization increased not only above-ground tissue P levels, but Farmaha et al. (2011a) also reported a similar increase in seed P concentration for this study. Our tissue K results also agree with Fernández et al. (2009) who indicated an increase in tissue K concentration and accumulation with increasing soil test levels above those needed to maximize yield. However, our results contrast others that have found no K accumulation in response to K fertilization for high and very high K testing soils (Heckman and Kamprath, 1995; Rehm, 1995; Buah et al., 2000). While K fertilization increased tissue K accumulation, our earlier findings (Farmaha et al., 2011a) showed that K fertilization rate did not increase K removal in seed in this study, which indicates that K fertilization only increased cycling of K from the soil to the crop. Others
have observed luxury K-consumption in above-ground soybean tissues in fields testing above K levels needed for optimum yield (Hanway and Weber, 1971; Fernández et al., 2009).

**Plant Growth Analysis**

The NTBC treatment reduced LAI relative to STDB starting at the early vegetative stages, though significant differences were detected starting at early reproductive stages (R1/R2) (Figure 4.6). The NTDB treatment produced intermediate values relative to the other treatments and had significantly lower LAI values than STDB only at R2/R4 development stage. To our knowledge there are no reports comparing soybean growth components for no-till and strip-till treatments; but a study by Yusuf et al. (1999) comparing soybeans grown in no-till and conventional tillage contrasts our results since they observed differences in LAI due to tillage during early development stages. A possible explanation for this difference is that our study was planted approximately a month later compared to their study. Typically, differences in crop growth associated with tillage treatments are more evident due to cooler and wetter early-season conditions. Additionally, Farmaha et al. (2011b) reported for this study that compared to the no-till treatments the STDB treatment contained greater soil water at the BR position in the top 10 cm of the soil where most of the apparent nutrient uptake occurred. This difference was accentuated during the driest portions of the 2008 and 2009 growing seasons. These driest periods also coincide with the period of highest nutrient accumulation, as observed in Tables 4.3 and 4.4. Greater water availability in STDB compared to the no-till treatments during these stressful periods, when nutrient demands of the crop are high and soil water is limiting, likely resulted in the observed larger treatment differences emerging later in development.

For all tillage/fertilizer placement treatments LAI increased up to the R4/R5 development stage with the highest values being 4.1 for STDB and NTDB and 3.8 for NTBC, after which it
decreased. This finding agrees with Fernández et al. (2009) that also observed a continuous increase in LAI till R4/R5 with no further increase thereafter. Compared to the R4/R5 development stage, LAI measured at R6 stage had decreased by 7% in NTBC and 8% in NTDB, while during the same period, LAI had declined by 15% in STDB, with the most noticeable decline during the period R5-R6. While there was a large decline in LAI for STDB between R5 and R6, dry matter accumulation remained constant during that period (Figure 4.3), likely indicating dry biomass accumulation in seed. Maintenance of LAI for the no-till treatments during seed fill possibly indicates that those plants were using a greater proportion of photo assimilates to maintain leaf area instead of increasing seed fill relative to STDB. A possible support for this assumption comes from the study of Anderson and Vasilas (1985), conducted in central Illinois with late-planted soybeans that seed yield reduction occurred due to a decline in the sink to source ratio caused by lower rates of vegetative dry matter remobilization to the seed during the seed-fill period. In our study, maintenance of leaf area to a greater extent during the seed-fill period with no-till treatments compared to STDB likely resulted in the lower seed yields previously reported (Farmaha et al., 2011a) for the no-till treatments.

Soybean LAI increased in response to K fertilization during early vegetative stages but no differences were observed for P treatment (data not shown). At V1 the 168 kg K ha⁻¹ yr⁻¹ rate had produced a LAI of 0.24 which was 14% greater than that of the 0 kg K ha⁻¹ yr⁻¹ rate (check). While treatment differences became smaller as the plant developed, at the R4/R5 development stage the 168 kg K ha⁻¹ yr⁻¹ rate still produced a significantly 6% greater LAI than the check plots. While soybean plants have relatively low K accumulation during early development stages, the fact that LAI was influenced by K fertilization even in a soil with adequate K levels highlights the importance of K fertilization to enhance leaf development. Similarly, on a P and K
placement study, Borges and Mallarino (2000) indicated that fertilization effects were observed early in development. Fernández et al. (2009) also observed increased LAI with high-K testing soils compared to low-K testing soils and indicated that enhancing leaf expansion by adequate early-season K supply provided a competitive advantage to soybean. Besides the importance of adequate leaf expansion to maximize light interception and photosynthetic production, a large canopy can also have the added benefits of reducing solar radiation to the soil surface which lowers soil water evaporation and suppressing weed competition (Yelverton and Coble, 1991; Tesfaye et al., 2006).

Between the V2 and R6 development stages, SLW was fairly constant ranging from 30 to 37 g m$^{-2}$. The 168 kg K ha$^{-1}$ yr$^{-1}$ rate consistently produced smaller SLW values than the 0 kg K ha$^{-1}$ yr$^{-1}$ rate. Averaged across the growing season the 168 kg K ha$^{-1}$ yr$^{-1}$ rate produced a SLW of 30.8 g m$^{-2}$, which was 4% lower than that of the 0 kg K ha$^{-1}$ yr$^{-1}$ rate. While the specific physiological mechanisms for K rate treatment differences were not evaluated in this study, it is well known that K is important in osmotic adjustment and intracellular turgor pressure needed for cell expansion (Marschner, 1995). It is possible that greater SLW in the 0 kg K ha$^{-1}$ yr$^{-1}$ rate may be the result of a decrease in plant turgor pressure and cell size due to lower tissue K concentrations compared to higher K rates (Table 4.4).

Serial sampling makes growth component analysis inherently highly variable (Radford 1967). While we could not assign many statistical differences due to tillage/fertilizer placement treatment, CGR was numerically greater for STDB than NTBC across most of the growing season (Figure 4.7). Averaged across the growing season (V1-V2 to R4/R5-R5) CGR in STDB was numerically 15% greater than the NTBC treatment. During the last sampling interval (R5-R6) CGR for STDB was numerically 50% lower than NTBC and NTDB. This large (76%)
decline in STDB during the last sampling interval follows the trend observed for LAI and dry matter accumulation previously discussed. As with CGR, differences in NAR were not sufficiently large to establish statistical difference due to tillage/fertilizer placement treatment (Data not shown). However, we observed that NAR was 5.8 g m$^{-2}$ day$^{-1}$ for STDB and numerically, 33% higher than NTBC during the V1-V2 development stage interval. Averaged across all three tillage/fertilizer placement treatments NAR declined as LAI increased. This decline in NAR with increasing LAI was likely the result of greater mutual shading of leaves. Despite this decline in NAR, CGR overall increased across the growing season. Since CGR is the product of NAR and LAI (Hunt, 1982), the increase in CGR indicates that the rate of increase in LAI was greater than the rate of decline in NAR. These data illustrate that for the conditions of this study, increasing leaf area at the expense of some reduction in sunlight assimilation efficiency was overall beneficial as CGR was increased.

**CONCLUSIONS**

Strip-till deep band placement treatment produced greater protein and oil yield than with no-till treatments in response to seed yield as protein and oil concentrations were unaffected by tillage/fertilizer placement treatment. Increased P and K fertilization rates increased their concentrations in tissue but only P fertilization translated into greater seed P concentration. Increased dry matter accumulation, phosphorus accumulation, canopy height, and LAI with STDB treatment during the reproductive stage compared to no-till treatments could be associated with improved soil water content which increased P availability in the soil. Deep placement of P and K did not make an impact on plant growth and tissue nutrient levels compared to broadcast applications suggesting no disadvantage for vertical stratification of P and K under the conditions of this study. However, our findings indicate that overall better plant growth and
nutrient accumulation with STDB could result in increased productivity relative to the no-till treatments.

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### Table 4.1. Analysis of variance for soybean seed protein and oil concentration and yield over three years (2007-2009).

| Source of variation                      | df†  | Seed protein concentration |          | Seed oil concentration |          | Yield |          | Seed oil |          | Yield |          |
|------------------------------------------|------|----------------------------|----------|------------------------|----------|-------|----------|----------|-------|-------|
|                                          |      | concentration |          |                        |          | yield |          | yield |       |       |
|                                          |      | F Pr > F |          | F Pr > F |          | F Pr > F |          | F Pr > F |       |       |
| Tillage/fertilizer placement (T)         | 2    | 2.92    | 0.17     | 34.96     | <0.01    | 3.15  | 0.15     | 40.75   | <0.01 |
| Phosphorus fertilization (P)             | 3    | 12.31   | <0.01    | 12.21     | <0.01    | 7.86  | <0.01    | 5.22    | <0.01 |
| T × P                                    | 6    | 2.04    | 0.11     | 2.55      | 0.06     | 1.92  | 0.13     | 1.81    | 0.14  |
| Potassium fertilization (K)              | 3    | 4.67    | <0.01    | 4.97      | <0.01    | 9.07  | <0.01    | 2.94    | 0.03  |
| T × K                                    | 6    | 1.8     | 0.10     | 1.58      | 0.15     | 0.82  | 0.56     | 1.96    | 0.07  |
| P × K                                    | 9    | 1.05    | 0.40     | 0.62      | 0.78     | 1.01  | 0.43     | 0.71    | 0.70  |
| T × P × K                                | 18   | 0.51    | 0.95     | 0.76      | 0.74     | 0.78  | 0.72     | 0.84    | 0.65  |
| Contrast†                                 | 1    | 24.57   | <0.01    | 13.28     | 0.02     | 0.0   | 0.96     | 1.24    | 0.28  |
| 2007 – 2008                               | 1    | 18.18   | 0.01     | 136.18    | <0.01    | 554.91| <0.01    | 763.43  | <0.01 |
| 2007 – 2009                               | 1    | 85.0    | <0.01    | 64.62     | <0.01    | 556.78| <0.01    | 698.02  | <0.01 |
| 2008 – 2009                               |      |          |          |          |          |       |          |         |       |

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

¶ Contrast between years.
Table 4.2. Three-year (2007-09) mean soybean seed protein and oil concentration and yield as affected by tillage/fertilizer placement [no-till broadcast (NTBC), no-till deep band placement (NTDB) and strip-till deep band placement (STDB)] and P and K fertilization rate.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Seed protein concentration (g kg(^{-1}))</th>
<th>Seed oil concentration (g kg(^{-1}))</th>
<th>Seed oil yield (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tillage/fertilizer placement</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTBC</td>
<td>325 a†</td>
<td>900 c</td>
<td>194 a</td>
</tr>
<tr>
<td>NTDB</td>
<td>330 a</td>
<td>945 b</td>
<td>191 a</td>
</tr>
<tr>
<td>STDB</td>
<td>326 a</td>
<td>997 a</td>
<td>192 a</td>
</tr>
<tr>
<td><strong>Phosphorus fertilization rate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kg P ha(^{-1})yr(^{-1}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>327 a</td>
<td>927 b</td>
<td>193 ab</td>
</tr>
<tr>
<td>12</td>
<td>323 b</td>
<td>918 b</td>
<td>194 a</td>
</tr>
<tr>
<td>24</td>
<td>329 a</td>
<td>970 a</td>
<td>192 bc</td>
</tr>
<tr>
<td>36</td>
<td>329 a</td>
<td>974 a</td>
<td>191 c</td>
</tr>
<tr>
<td><strong>Potassium fertilization rate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kg K ha(^{-1})yr(^{-1}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>328 a</td>
<td>968 a</td>
<td>191 c</td>
</tr>
<tr>
<td>42</td>
<td>327 ab</td>
<td>946 ab</td>
<td>192 b</td>
</tr>
<tr>
<td>84</td>
<td>328 ab</td>
<td>946 ab</td>
<td>192 b</td>
</tr>
<tr>
<td>168</td>
<td>325 b</td>
<td>929 b</td>
<td>193 a</td>
</tr>
</tbody>
</table>

† Means within a column and treatment, followed by the same letter are not significantly different.
Table 4.3. Two-year (2008-09) mean soybean above-ground plant tissue P concentration and accumulation at different development stages as affected by phosphorus fertilization rate.

<table>
<thead>
<tr>
<th>Development stage</th>
<th>V1</th>
<th>V2</th>
<th>V4/R1*</th>
<th>R1/R2</th>
<th>R2/R4</th>
<th>R4/R5</th>
<th>R5</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus fertilization rate (kg P ha(^{-1}) yr(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3.2 c †</td>
<td>3.6 c</td>
<td>3.1 c</td>
<td>3.1 c</td>
<td>3.0 a</td>
<td>2.7 b</td>
<td>2.3 b</td>
<td>2.1 b</td>
</tr>
<tr>
<td>12</td>
<td>3.6 b</td>
<td>3.8 b</td>
<td>3.3 ab</td>
<td>3.3 b</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>3.7 ab</td>
<td>3.8 b</td>
<td>3.3 b</td>
<td>3.3 b</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>3.9 a</td>
<td>4.0 a</td>
<td>3.4 a</td>
<td>3.4 a</td>
<td>3.1 a</td>
<td>3.0 a</td>
<td>2.6 a</td>
<td>2.4 a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phosphorus accumulation (kg P ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>24</td>
</tr>
<tr>
<td>36</td>
</tr>
</tbody>
</table>

† Means within a column, followed by the same letter are not significantly different.
* Left to / sign, indicates development stage in 2008 and right to / sign, indicates growth stage in 2009.
Table 4.4. Two-year (2008-09) mean soybean above-ground plant tissue K concentration and accumulation at different development stages as affected by potassium fertilization rate.

<table>
<thead>
<tr>
<th>Development stage</th>
<th>V1</th>
<th>V2</th>
<th>V4/R1*</th>
<th>R1/R2</th>
<th>R2/R4</th>
<th>R4/R5</th>
<th>R5</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium fertilization rate (kg K ha⁻¹ yr⁻¹)</td>
<td>0</td>
<td>22.4 d †</td>
<td>25.6 b</td>
<td>22.3 c</td>
<td>22.4 d</td>
<td>21.4 b</td>
<td>20.1 b</td>
<td>15.9 b</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>26.6 c</td>
<td>29.0 a</td>
<td>25.3 b</td>
<td>25.6 c</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>84</td>
<td>27.9 b</td>
<td>29.7 a</td>
<td>26.3 a</td>
<td>26.8 b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>168</td>
<td>30.0 a</td>
<td>30.0 a</td>
<td>27.1 a</td>
<td>28.1 a</td>
<td>27.1 a</td>
<td>23.7 a</td>
<td>19.1 a</td>
</tr>
<tr>
<td>Potassium concentration (g K kg⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1.56 c</td>
<td>5.28 b</td>
<td>15.06 b</td>
<td>32.73 b</td>
<td>52.1 b</td>
<td>70.3 b</td>
<td>83.2 b</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>1.95 b</td>
<td>6.11 a</td>
<td>18.28 a</td>
<td>39.22 a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>84</td>
<td>2.13 a</td>
<td>6.45 a</td>
<td>18.55 a</td>
<td>39.90 a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>168</td>
<td>2.22 a</td>
<td>6.61 a</td>
<td>18.75 a</td>
<td>41.52 a</td>
<td>67.0 a</td>
<td>89.2 a</td>
<td>97.1 a</td>
</tr>
</tbody>
</table>

†Means within a column, followed by the same letter are not significantly different.

* Left to / sign, indicates development stage in 2008 and right to / sign, indicates growth stage in 2009.
Figure 4.1. Soybean protein yield as affected by tillage/fertilizer placement treatment [no-till/broadcast (NTBC), no-till/deep band (NTDB) and strip-till/deep band (STDB)] and phosphorus fertilization rate averaged over three years (2007-2009) and potassium fertilizer rates. [Seed protein yield\textsubscript{NTBC} = 874.8 + 1.4 * (P rate), R\textsuperscript{2} = 0.83, P =0.09; Seed yield\textsubscript{NTDB} = 904.1 + 2.26 * (P rate), R\textsuperscript{2} = 0.96, P =0.02; Seed yield\textsubscript{STDB} = 974.9 + 1.2 * (P rate), R\textsuperscript{2} = 0.20, P =0.55].
Figure 4.2. Relationship between soybean seed yield and protein yield (a) and with oil yield (b) at harvest, averaged across treatments over a three-year period (2007-2009). [Seed yield = 0.057 + 0.003 * (Protein yield), R² = 0.92, P = < 0.0001; Seed yield2007-08 = -0.166 + 0.005 * (Oil yield2007-08), R² = 0.98, P = < 0.0001; Seed yield2009 = 0.0176 + 0.006 * (Oil yield2009), R² = 0.89, P = < 0.0001].
Figure 4.3. Soybean total aboveground dry matter accumulation as affected by tillage/fertilizer placement [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)] at different development stages across the season and averaged over phosphorus and potassium fertilizer rate, and over two years (2008-2009). Left to / sign, indicates development stage in 2008 and right to / sign, indicates growth stage in 2009. * Sign indicates significant differences between at least two tillage/fertilizer placement treatments.
Figure 4.4. Volumetric soil water content ($\Theta_v$) by depth (0-5 and 5-10 cm) as affected by tillage/fertilizer placement [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)] and by sampling position with respect to the crop-row (IR, in-row; BR, between-rows) at different development stages across the season and averaged over phosphorus and potassium fertilizer rates (0-0 and 36-168 kg P-K ha$^{-1}$ yr$^{-1}$), and over two years (2008-2009). Left to / sign, indicates development stage in 2008 and right to / sign, indicates growth stage in 2009.
Figure 4.5. Soybean canopy height as affected by tillage/fertilizer placement [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)] at different development stages across the season and averaged over phosphorus and potassium fertilizer rate, and over two years (2008-2009). Left to / sign, indicates development stage in 2008 and right to / sign, indicates growth stage in 2009. * Sign indicates significant differences between at least two tillage/fertilizer placement treatments.
Figure 4.6. Soybean leaf area index (LAI) as affected by tillage/fertilizer placement [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)] at different development stages across the season and averaged over phosphorus and potassium fertilizer rate, and over two years (2008-2009). Left to / sign, indicates development stage in 2008 and right to / sign, indicates growth stage in 2009. * Sign indicates significant differences between at least two tillage/fertilizer placement treatments.
Figure 4.7. Soybean crop growth rate (CGR) as affected by tillage/fertilizer placement [no-till/broadcast (NTBC), no-till/deep band (NTDB), and strip-till/deep band (STDB)] at different development stage intervals across the season and averaged over phosphorus and potassium fertilizer rate, and over two years (2008-2009). Left to / sign, indicates development stage in 2008 and right to / sign, indicates growth stage in 2009. * Sign indicates significant differences between at least two tillage/fertilizer placement treatments.
CHAPTER 5

CONCLUSIONS

The study was designed to find the impact of phosphorus and potassium rate and placement with no-till and strip-till treatments on soybean [Glycine max (L.) Merr.] shoot growth and root distribution in the soil, seed yield and yield components, and seed composition; and to quantify treatment effects on the distribution of P, K, and water in the soil.

In the second chapter of this dissertation, we discussed findings showing greater yield and greater P and K removal with strip-till deep placement (STDB) compared to both no-till treatments [no-till broadcast (NTBC) and no-till deep placement (NTDB)]. We found no difference in yield due to fertilizer placement, but our data indicates that STDB can provide better growing conditions than the no-till treatments, possibly by increasing soil water infiltration and minimizing evaporation of that water once it is in the soil by maintaining crop residue cover in most of the soil surface. The effect of tillage on soybean seed yield can be readily observed especially when tillage variables were compared at the 0-0 kg P-K ha\(^{-1}\) yr\(^{-1}\) rate. Soybean seed yield was not limited by soil P level in STDB as it was in the no-till treatments. A linear decrease in soybean seed yield was observed for both no-till treatments with increase of K fertilization. In our study, it is not clear what factor or factors might have contributed to the observed decline in seed yield with K fertilization.

In the third chapter of this dissertation, we reported greater water availability in the top 10 cm of the soil in STDB compared to the other tillage/fertilizer placement treatments. This greater water availability likely made P more available to soybeans and
allowed roots to be more efficient at obtaining this nutrient under low soil concentrations. It was not only more soil water for STDB compared to other tillage/fertilizer placement treatments across the season on the top 10 cm where nutrient uptake is mostly occurring, but during the seed-fill period, when nutrient demands are greatest, differences in soil water content increased to 20%. We suspect differences in soil water content during the dry period have probably contributed to increased plant growth with STDB compared to other tillage/fertilizer placement treatments. Like large differences in soil water content occurred only at top soil surface, changes in soil P concentrations from 2007 to 2009 at R1 also mostly occurred at the top 5 cm where greater root densities were observed.

Within the top 5 cm of soil depth, soil P levels decreased more at the between-row (BR) position where water availability was also greater in STDB relative to NTBC and NTDB. Although most of the apparent nutrient uptake seems to occur on the soil surface, P and K test levels also decreased at the deeper layers of the soil especially for STDB, which indicates that roots may be extracting nutrients from the entire rooting depth and not just where fertilizers are applied.

Surface broadcast applications of P and K fertilizers increased the degree of vertical stratification with higher P and K levels in the surface than the subsurface. Conversely, deep banding of fertilizer increased soil P and K levels at the in-row (IR) position in the subsurface and created a horizontal pattern of higher and lower concentrations across the field. We observed that deep banding of fertilizers reduced P and K surface soil test levels over the duration of this study but deep placement caused no yield reductions relative to broadcast applications. This would indicate that deep
placement of fertilizers may be advantageous for soybean production in fields where the potential of surface P runoff poses a risk for environmental degradation.

In the fourth chapter of this dissertation, we discussed the fact that STDB produced greater dry matter accumulation, canopy height, leaf area index (LAI), and crop growth rate (CGR) than in the NTBC and NTDB treatments. These differences translated into greater protein and oil yield, which were a reflection of greater seed yield with STDB than NTBC since protein and oil concentrations were unaffected. This indicates that management objective to increase yield quality (oil and protein) may not be different than management objectives to improve seed yield.

Greater P accumulation in the tissues was found with STDB compared to NTBC and NTDB produced intermediate values compared to the other two treatments. The differences in tissue P accumulation could relate to greater dry biomass accumulation as tissue P concentrations remains unchanged among different tillage/fertilizer placement treatments across the growing season. Furthermore, soil P test levels decreased over three years substantially and significantly only from top soil surface for no-till treatments, but for STDB treatments, soil P test levels decreased significantly from all the depths within 40 cm of the soil profile. So, we suspect increased dry matter and tissue P accumulation with STDB compared to other tillage/fertilizer placement treatments related with increased soil water and P availability in the 40 cm of the soil profile. Tissue K concentration and tissue P concentration increased with increasing P and K fertilization rate, respectively, but not with the placement of P and K fertilizers.
IMPLICATIONS OF THIS WORK

Conservation tillage practices are very important in Illinois. While no-till treatments may provide benefits to the environment and farmers, there are some challenges with this system, especially as it relates to crop residue after corn (Zea mays L.). Normally, the greatest challenge with crop residue is for planting corn after a previous corn crop because this crop is generally planted earlier relative to soybean. Earlier planting sometimes is not possible due to wetter and cooler soil conditions under heavy crop residue. For these reasons studies on alternative conservation tillage systems, such as strip-till, have been focused on corn production. However, typically there are more hectares in corn-soybean production systems than in corn-corn. Further, recent studies have shown the benefit of early-season soybean planting (De Bruin and Pedersen, 2008), but the options are limited to do so. Thought, the use of strip-till provides a viable option for early-season planting, it but its utility for soybean has not looked in details. The numbers of studies showing soybean seed-yield advantage with strip-till are limited and also these studies do not provide enough details to reason out the differences in soybean seed yield. Like strip-till studies, little has been done to determine the potential benefits of deep placement of P and K fertilizers to increase soybean production. Our aim was to determine if there was a benefit associated with the treatments of this study and to try to quantify how or where the benefit was. We determined that the STDB system provided greater soil water availability, which facilitated nutrient accumulation and overall greater above-ground growth and seed yield. These benefits are realized without deep band placement of fertilizers. However, deep band-placement may be advantageous for fields where it may be important to reduce soil surface P levels to minimize the
potential negative environmental impact of surface P runoff. While we cannot determine what yield differences would have been possible with a broadcast application of fertilizer in strip-till, it is important to realize that the unfertilized STDB treatments produced higher seed yields than the NTDB and NTBC treatments that received fertilizer. With this caveat in mind, this study may be important to farmers that would consider strip-till as an alternative, but the added cost of a dry fertilizer applicator unit is too much of a deterrent for them to consider strip-till as an option.

LIMITATIONS OF THIS WORK

This study was very comprehensive in nature since we investigated treatment effects not only in terms of the final outcome (seed yield) but we tried to quantify with various measurements (such of root parameters, soil P and K levels, soil water, growth and yield components, nutrient uptake, and seed composition) how the treatments brought about the differences measured at the end of the season. While this study has produced useful and relevant information, in my view there are some limitations:

- Since, this study was conducted only at one location with two soil types (studied together), two cultivars, and for three years, our inference space is limited and we are not able to draw conclusive recommendations applicable to a broader geography or set of conditions.

- This study was designed to compare broadcast versus deep band placement of P and K fertilizers in a no-till system and to study the potential benefits of strip-till deep band placement. This study lacks a strip-till broadcast treatment that would have allowed us to determine whether nutrient placement is important for strip-till.
In the literature, one of the reported benefits of strip-till has been the fact that this system can help with better germination and early plant growth and nutrient uptake. In two out of three years, planting was done in late June, thus limiting our capacity to measure these potential benefits. In addition, strip-till is normally recommended as a fall, not a spring-tillage system. Due to wet soil conditions in the fall and other logistical problems, this study was conducted as a spring-tillage project, potentially limiting the use of this information for a more traditional fall-tillage system.

In 2009, due to a large delay in planting, a different soybean variety was used. This can confound our results since we are not able to separate any genotype difference in the data from that particular year.

We found that there was marginal yield reduction with K fertilization, in particular with the NTDB system. We did not collect roots data during germination or early growth stages to quantify whether there was salt injury due to the concentrated fertilizer band.

Due to practical constraints, yield components and plant samplings were done only from a 0.5 m² area. A larger sampling area could have improved our ability to capture more accurately the inherent variability present in this type of measurements.

Response to fertilizer rate was limited for P and there was no response to K rate. This was an artifact of the fertility status of the study site. It is expected that continuation of these treatments in future years will result in a greater range of response. This limitation highlights the importance of establishing and
maintaining long-term studies that can provide distinct soil conditions to more effectively evaluate the desired treatments.

- Deep banding reduced the pattern of decreasing P and K levels with increasing depth compared to the broadcast treatments, but increased the differences in horizontal distribution of those nutrients across the field. This pattern of areas with high P and K fertility followed by areas of low fertility across the field can make it difficult to accurately determine the fertility of a field by traditional soil sampling schemes.

FUTURE RESEARCH OPPORTUNITIES

This study has laid a good foundation for additional studies on strip-till and nutrient fertilizer placement. Some of the research opportunities to test the use of strip-till and placement of P and K fertilizers for soybean production are listed below.

- In order to establish a recommendation system related to the use of strip-till and nutrient placement for this tillage operation, similar studies to the one presented in this dissertation should be conducted using different soybean varieties and different locations around the state involving very low, low, medium, high, and very high P and K testing soils.

- Placement of P and K was tested only at 15 cm of depth for strip-till. Including additional depths, even surface broadcast applications, can be important to better understand the potential benefit of the various placement methods. Additionally, this study was done with applications occurring at the exact or near exact location every year. It would be important to study the benefits of changing the location of the fertilizer band. This can in essence eliminate the problem of horizontal P and K stratification for sampling collection mentioned earlier.
Since we did not observe response to P and K fertilization in our study under STDB and yields were higher than the other tillage/fertilizer placement treatments even without fertilization, a possible study would be to determine whether increasing soybean plant population can produce higher yields with strip-till.

Soil P levels indicated that P was limiting soybean production. However, we found no correlation between tissue nutrient content at the recommended sampling time (R1 development stage) and final seed yield. This highlights the need to further investigate whether the existing soil and tissue nutrient levels recommended for soybean production are still adequate for new soybean genotypes.

Additional work is needed to test strip-till for early soybean planting and to quantify the potential benefits of this system in relation to soil water and nutrient availability and temperature early in the season.

Tissue carbohydrate analysis could help explain translocation of photosynthate.

Additional sampling to measure soil water infiltration, soil temperature especially early in the season, and more intensive measurements on nutrient availability and roots development in the season would help to critically examine some to the issues associated with tillage and placement studies.

The extensive dataset generated from this project can be further utilized for crop growth modeling with different scenarios of agronomic practices with changing weather scenarios.
CURRICULUM VITAE

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EDUCATION

University of Illinois – Urbana/Champaign

○ Ph.D., Crop Sciences, 2011 (Advisor: Dr. Fabián G. Fernández.).

Thesis Title: Strip-till and no-till soybean growth and distribution of roots and soil phosphorus, potassium, and water with broadcast and subsurface-band fertilization.

Punjab Agricultural University, India


Thesis Title: Integration of model for nitrate movement in soil-aquifer with Geographic Information System (GIS).


RESEARCH EXPERIENCE

University of Illinois – Urbana/Champaign


Punjab Agricultural University, India


AWARDS AND RECOGNITIONS

- Gerald O. Mott Meritorious Graduate Student Award by Crop Science Society of America, USA, 2011.
- Outstanding Graduate Student Award by North Central Extension-Industry Soil Fertility, 2009.
- Graduate Student travel Award by ASA-CSSA-SSSSA, Houston, TX, 2008.
- Graduate Student travel Award by Deptt. of Crop Sciences, UIUC, 2007.
- Best Post Graduate thesis award (2005) at National Award by Indian Society of Agricultural Engineers, India in the field of Agricultural Engineering.
- Dr. Duleep Singh Deep Memorial Award - 2002, Best student of the University for Social Welfare and communal Harmony – M Tech, PAU, India.

PUBLICATIONS AND PRESENTATIONS

I. Refereed journal articles:


II. Non-refereed research articles, technical reports, and proceedings: 2

III. Published abstracts: 6

IV. Extension Publications: 1

V. Presentations: 6