ABSTRACT

Multiple years of phosphorus (P) fertilizer application may be needed before the agronomic and environmental effect of P fertilizer placement and application rate become noticeable. The objective of this study was to evaluate the long-term effects of P placement on corn (*Zea mays* L.) with strip-tillage. The study was conducted for 10 yr at two locations in Kansas in a corn and soybean (*Glycine max* L.) rotation from 2006 to 2015. Strip-tillage was conducted before corn and soybean were planted without previous tillage. Phosphorus fertilizer placement and rate treatments included a control, broadcast at 20 kg P ha\(^{-1}\) and 39 kg P ha\(^{-1}\), deep-band at 20 kg P ha\(^{-1}\) and 39 kg P ha\(^{-1}\), in a factorial combination with two starter fertilizer treatments (with and without starter fertilizer). Response parameters included V6 whole plant P uptake, ear leaf P, grain P concentration, and yield. Phosphorus fertilizer increased crop response parameters when compared to the control including yield for some years or across years at the two locations. However, corn response was similar among the P rate-place treatments with generally higher values for the P rate of 39 kg P ha\(^{-1}\). The use of starter fertilizers in combination with broadcast or deep-band P fertilizer resulted in greater P uptake, ear leaf P and grain P; however only increased yield at one location. Results from this study showed similar corn yield for deep-band and broadcast P fertilizer under strip-tillage and starter fertilizer increased yield for a high-yielding, low soil test P location.

Core Ideas

- Results showed a significant effect of P fertilizer rate and placement in early season whole plant P uptake, ear leaf P concentration, grain P concentration, and yield over the course of this study but particularly after multiple years of treatment application.
- Early P uptake in corn was consistently higher with deep band P fertilizer applications and with starter fertilizer with the planter.
- The long-term evaluation of P fertilizer placement showed that deep-band P placement only seldom resulted in higher yields. The use of starter fertilizer increased average grain yield, particularly for high-yielding systems.

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C.L. Preston, D.A. Ruiz Diaz, and D.B. Mengel

Strip-tillage allows for residue to be incorporated in a narrow band and prepares the soil for planting. Deep-band application of fertilizer with the strip-tillage operation concentrates nutrients directly below the planted seed. This fertilizer placement can provide a competitive advantage for plant nutrient uptake while minimizing potential nutrient losses by runoff (Fernández and White, 2012). The use of plant tissue testing to monitor P uptake early in the season has shown the greatest recovery of P with band applications (Schwab et al., 2006). However, this increase in P recovery has not necessarily translated into increased corn grain yield compared to broadcast (Barber, 1980; Mallarino et al., 1999). On the other hand, P stratification with surface broadcast in reduced tillage systems can potentially affect crop yield due to lack of nutrient acquisition (Mallarino and Borges, 2006). Nutrient stratification can be increased with the lack of incorporation of nutrients (Robbins and Voss, 1991) and excessive crop residue (Karlen et al., 1991). Therefore, in reduced tillage systems, P fertilizer placement may be particularly relevant.

Phosphorus stratification from surface P fertilizer applications is often a concern for crop nutrient uptake, particularly with limited soil moisture near the surface (Eckert and Johnson, 1985; Mullen and Howard, 1992; Fernández and Schaefer, 2012). However, previous studies have shown that broadcast applications can produce similar or higher grain yields compared to banding (Bordoli and Mallarino, 1998). Broadcast fertilizer application can result in greater soil volume entering in contact with the fertilizer. Kovar and Barber (1989) showed that the greatest plant P recovery occurred when five percent or more of the soil volume was fertilized.

The use of starter fertilizers creates an area of concentrated P fertilizer near the plant roots early in the season. Some studies showed a consistent corn yield response with 5 cm to the side and 5 cm below the seed applications (Randall and Hoefl, 1988). The combination of broadcast and band application could improve crop uptake as the band-applied P fertilizer would allow for readily available P early in the season, and broadcast could increase nutrients throughout the surface portion of the soil. Previous studies have also shown changes in root growth with different P fertilizer placements, affecting crop response under drought stress conditions (Hansel et al., 2017a; Hansel et al., 2017b). Several studies have compared P fertilizer placement methods, including starter applications, broadcast,
and deep-band (Walker et al., 1984; Rehm, 1986). However, a limited number of studies evaluated placement methods over multiple years and the long-term effect of repeated fertilizer applications on corn response.

Soil test P (STP) levels can have a significant effect on corn response to P fertilizer rate and placement. Yield response to P fertilizer placement is small or nonexistent when STP is close to optimum values providing flexibility for P fertilizer placement (Mallarino et al., 1991; Mallarino and Blackmer, 1992; Webb et al., 1992). However, under very low STP, corn grain yield may be affected by the use of P starter fertilizers, broadcast or deep-band P (Rehm, 1986). The vertical and horizontal stratification of soil test P after multi-year P fertilizer placement with strip tillage might also affect corn response to subsequent P fertilization, generating the need for the long-term evaluation of P fertilizer placement on under strip-tillage system in corn. The objective of this study was to evaluate the long-term effect of P fertilizer placement and application rate for corn grown in rotation with soybean under a strip-tillage system.

**MATERIALS AND METHODS**

Long-term research trials were established in Ottawa and Scandia, Kansas in 2006. The soil at the Ottawa location (38°32′19″ N, 95°15′11″ W) was classified as Woodson silt loam (fine, montmorillonitic, thermic, Abruptic Argiaquoll) (Soil Survey Staff, 2014). The soil at the Scandia location (39°46′23″ N, 97°47′19″ W) was classified as a Crete silt loam (fine, smectitic, mesic Pachic Argiustolls) (Soil Survey Staff, 2014). The Scandia location had a history of no-till production practices for approximately 5 yr before the implementation of this study, while the Ottawa location was managed with conventional tillage before the implementation of the study. The Scandia location received supplemental irrigation, and Ottawa was rain-fed. A 2-yr corn–soybean rotation was used at both locations, and each phase of the rotation was present every year in the study. Corn was seeded at 66,716 and 79,071 seeds ha⁻¹ in Ottawa and Scandia, respectively. Corn planting dates during the 10 yr of the study were between April-15 and May-15 at both locations. Both locations received strip-tillage before corn, whereas soybean was planted directly into the corn residue with no prior tillage. The spacing from strip center to center was 76 cm, and corn was planted in the center of the strip. Corn and soybean were both planted in the row of the previous years’ crop. The plot size was 3.0 m wide (four rows) by 15 m long.

The experimental design was a factorial in a randomized complete block design with four replications. The factorial arrangement was a 2 × 5 with the main effects of two starter and five placement-rate fertilizer combinations. The main effect of starter fertilizer included: (i) with starter fertility and (ii) without starter fertilizer. The main effect placement-rate included: (i) with starter fertility and (ii) without starter fertility. The main effect rate included: (i) control with no P application; (ii) broadcast at 20 kg P ha⁻¹; (iii) broadcast at 39 kg P ha⁻¹; (iv) deep-band at 20 kg P ha⁻¹; and (v) deep-band at 39 kg P ha⁻¹. The starter fertilizer application rate was 10 kg P ha⁻¹ (20 lbs. P₂O₅ acre⁻¹), and the balance was applied as broadcast or deep-band to bring the total application rate to either 20 or 39 Kg P ha⁻¹ (40 and 80 lbs. P₂O₅ acre⁻¹ respectively). At the Ottawa and Scandia locations, the starter fertilizer was applied 5 cm to the side and 5 cm below the seed (5 × 5) with the planter using liquid ammonium polyphosphate (APP), 10–15–0 (N–P–K) (10–34–0, N–P₂O₅–K₂O). Broadcast treatments were applied by hand to the soil surface before planting using dry triple superphosphate (TSP), 0–20–0 (N, P, K) (0–45–0; N–P₂O₅–K₂O). Deep-band applications were applied with the strip-till operation at approximately 15 cm below the soil surface before corn planting using APP at both locations.

The implement used in Scandia was a Brothers Equipment Inc. (Friend, NE) strip-till unit with straight chisel point shank knife, wave coulter, rolling basket, and fertilizer application with John Blue (John Blue Company, Huntsville, Alabama) ground driven pump. The strip-till implement used in Ottawa was a Yetter Brand (Yetter Manufacturing Company, Colchester, IL) with Maverick wavy openers (model 2984) set up with 5 cm mole knives and straight coulters reversed for settling strips with a John Blue (John Blue Company, Huntsville, Alabama) ground driven pump for fertilizer application. All plots in the study were strip-tilled to prevent tillage effects, even if no P fertilizer was applied. Nitrogen (N) was applied in a deep-band placement with urea ammonium nitrate (UAN) (28–0–0; N–P–K) to balance N in all treatments. In Ottawa, 134 kg N ha⁻¹ yr⁻¹ was applied before corn as a deep-band using UAN with the strip-till operation. From 2006 to 2010 in Scandia, the total application rate of N was 190 kg ha⁻¹ yr⁻¹ using UAN and applied with the strip-till operation. From 2011 to 2015 a blanket application of 224 kg N ha⁻¹ was made using anhydrous ammonia (AA) (82–0–0; N, P, K) and 27 kg N ha⁻¹ to balance N in the deep-band for a total of 251 kg N ha⁻¹.

Initial soil samples were collected in the fall of 2005, before initiating the study by collecting one composite sample of 15 cores taken randomly in the study area to get a representative sample at the 0–15 cm sampling depth. Soil pH was determined in a 1:1 soil:water mixture. Soil test P (STP) levels were determined colorimetrically using the Mehlich-3 extraction (Frank et al., 1998) with a 300 series Alphkem Rapid Flow Analyzer, and soil test potassium (STK) was determined by ICP–OES (inductively coupled plasma optical emission spectrometry) using the ammonium acetate extraction (Warncke and Brown, 1998). Organic matter was determined by Walkley-Black (Combs and Nathan, 1998).

Soil samples were collected in late fall/winter of 2015 after corn and soybean harvest for five selected treatments (control, broadcast, broadcast + starter, deep-band, and deep-band+ starter at the 39 kg P ha⁻¹ rate). Separate samples were collected from in-row and between-row areas at the 0–15 cm depth. For the in-row sampling composite subsamples were collected from the row as well as 7.6 and 15 cm away from the center of the row. For the between-row sampling (where no strip-tillage had occurred), composite subsamples were collected from the row-middles as well as 7.6 and 15 cm away from the row-middles. A total of 8 individual cores were collected for each sampling point. Samples were air-dried, ground and analyzed for STP by the Mehlich-3 extraction (Frank et al., 1998).

Daily total precipitation and air temperature data were collected for each location using automated weather stations located within one kilometer from the study area (Table 1). Ten above-ground whole-plant samples were taken at the V6 growth stage (Ransom and George, 2013), and fifteen corn ear leaf (the leaf attached to the uppermost ear) samples were collected at the
R2 growth stage from the two outer rows. Plant samples were dried in a forced air oven at 60°C for a minimum of 4 d, and dry weight was recorded for the V6 whole-plant samples. Afterward, dry plant samples were ground with a Wiley Mill grinder to pass a 2 mm screen. Tissue samples were digested with sulfuric acid, and hydrogen peroxide digest (Thomas et al., 1967) and P concentration were determined by ICP–OES (inductively coupled plasma optical emission spectrometry). Whole plant dry biomass and P concentration were used to calculate total P uptake at the V6 growth stage. The two center rows of each plot were harvested with a plot combine. Grain weight was recorded and adjusted to 155 g kg⁻¹ moisture. Grain samples were ground to pass a 2 mm screen, digested and analyzed for P concentration following the same procedure as leaf sample analysis.

Analysis of variance was completed for place-rate and starter fertilizer main and interaction treatment effects on corn

Table 1. Yearly total precipitation, and average air maximum and minimum temperatures collected from an automated weather station located within one km from the experimental location.

<table>
<thead>
<tr>
<th>Year</th>
<th>Ottawa Precipitation‡</th>
<th>Ottawa Max temperature§</th>
<th>Ottawa Min temperature§</th>
<th>Scandia Precipitation</th>
<th>Scandia Max temperature</th>
<th>Scandia Min temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>°C</td>
<td>mm</td>
<td>mm</td>
<td>°C</td>
<td>mm</td>
</tr>
<tr>
<td>2006</td>
<td>812</td>
<td>20.9</td>
<td>7.67</td>
<td>680</td>
<td>19.8</td>
<td>5.13</td>
</tr>
<tr>
<td>2007</td>
<td>1271</td>
<td>19.1</td>
<td>7.22</td>
<td>975</td>
<td>18.2</td>
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<tr>
<td>2008</td>
<td>1135</td>
<td>17.6</td>
<td>5.67</td>
<td>1127</td>
<td>17.0</td>
<td>3.96</td>
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<tr>
<td>2009</td>
<td>1179</td>
<td>17.8</td>
<td>6.57</td>
<td>706</td>
<td>17.7</td>
<td>3.83</td>
</tr>
<tr>
<td>2010</td>
<td>1911</td>
<td>19.5</td>
<td>8.13</td>
<td>1442</td>
<td>18.2</td>
<td>6.18</td>
</tr>
<tr>
<td>2011</td>
<td>734</td>
<td>20.2</td>
<td>7.88</td>
<td>523</td>
<td>19.1</td>
<td>5.55</td>
</tr>
<tr>
<td>2012</td>
<td>536</td>
<td>22.5</td>
<td>8.83</td>
<td>415</td>
<td>20.9</td>
<td>5.61</td>
</tr>
<tr>
<td>2013</td>
<td>734</td>
<td>17.9</td>
<td>5.87</td>
<td>571</td>
<td>17.7</td>
<td>4.46</td>
</tr>
<tr>
<td>2014</td>
<td>687</td>
<td>18.2</td>
<td>5.96</td>
<td>482</td>
<td>17.8</td>
<td>4.69</td>
</tr>
<tr>
<td>2015</td>
<td>962</td>
<td>19.6</td>
<td>7.38</td>
<td>702</td>
<td>19.3</td>
<td>5.72</td>
</tr>
</tbody>
</table>
| Avg† | 996                   | 19.3                     | 7.12                     | 732                   | 18.5                     | 5.04                     | 30-yr normal 1024 18.7 6.67 732 18.1 5.11

† 10-yr average total precipitation and average maximum and minimum temperatures.
‡ Precipitation total by year.
§ Average maximum and minimum air temperatures measured at 2 m above ground.

Table 2. Significance of F values for the main effects of starter (ST) and place-rate (PR), and the interaction of ST × PR on P uptake in whole plant samples taken at the V6 growth stage and P concentration in corn ear leaf collected at the R2 growth stage at the Ottawa and Scandia locations for the 10-yr study and average across years.†

<table>
<thead>
<tr>
<th>Year</th>
<th>Ottawa V6 P uptake</th>
<th>Ottawa Ear leaf P</th>
<th>Scandia V6 P uptake</th>
<th>Scandia Ear leaf P</th>
<th>Ottawa ST × PR</th>
<th>Ottawa Place-rate</th>
<th>Ottawa ST × Place-rate</th>
<th>Scandia ST × PR</th>
<th>Scandia Place-rate</th>
<th>Scandia ST × Place-rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P &gt; F</td>
<td>P &gt; F</td>
<td>P &gt; F</td>
<td>P &gt; F</td>
<td>P &gt; F</td>
<td>P &gt; F</td>
<td>P &gt; F</td>
<td>P &gt; F</td>
<td>P &gt; F</td>
<td>P &gt; F</td>
</tr>
<tr>
<td>2007</td>
<td>0.220</td>
<td>0.399</td>
<td>0.924</td>
<td>0.001</td>
<td>0.001</td>
<td>0.060</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2008</td>
<td>0.472</td>
<td>0.435</td>
<td>0.372</td>
<td>0.001</td>
<td>0.373</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2009</td>
<td>0.001</td>
<td>0.001</td>
<td>0.058</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2011</td>
<td>0.001</td>
<td>0.026</td>
<td>0.202</td>
<td>0.001</td>
<td>0.060</td>
<td>0.277</td>
<td></td>
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<tr>
<td>2012</td>
<td>0.334</td>
<td>0.128</td>
<td>0.151</td>
<td>0.001</td>
<td>0.110</td>
<td>0.445</td>
<td></td>
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<tr>
<td>2013</td>
<td>0.001</td>
<td>0.012</td>
<td>0.372</td>
<td>0.001</td>
<td>0.001</td>
<td>0.164</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2014</td>
<td>0.001</td>
<td>0.303</td>
<td>0.074</td>
<td>0.001</td>
<td>0.003</td>
<td>0.289</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2015</td>
<td>0.001</td>
<td>0.019</td>
<td>0.922</td>
<td>0.017</td>
<td>0.003</td>
<td>0.152</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Across years‡</td>
<td>0.001</td>
<td>0.001</td>
<td>0.079</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† V6 P uptake, calculated P uptake as a function of biomass and P concentration; Ear Leaf P, P concentration in corn ear leaf samples taken at R2 growth stage.
‡ Significance of sample averaged across 10-years.
§ Whole plant samples were not collected in 2006 or 2010 in Ottawa or 2006, 2009, or 2010 in Scandia. Ear leaf samples were not collected in 2010 in Ottawa.
response parameters (P uptake, ear leaf P, grain P, and yield). Data analysis was completed for each location separately by year as well as analysis across years using PROC GLIMMIX in SAS 9.4 (SAS Inst. Inc., Cary, NC). Blocks were included as a random effect in the model, and analysis across years was completed including year as a random effect in the model with the first-order autoregressive covariance structure (Littell et al., 2006). Mean separation was completed using the LINES option in PROC GLIMMIX, and the SLICE option for the partition of interactions of the main effects. Statistical significance was determined when \( P < 0.10 \).

**RESULTS AND DISCUSSION**

The soil samples collected before initiating the study showed a pH of 5.8 and 6.6 for Ottawa and Scandia, respectively. The STP was 7.6 mg kg\(^{-1}\) for both locations, STK was 155 and 515 mg kg\(^{-1}\), and organic matter 29 and 26 g kg\(^{-1}\), for Ottawa and Scandia, respectively. The total precipitation and mean maximum and minimum air temperatures by year from 2006 to 2015 for both locations are shown in Table 1. The 10-yr mean precipitation at the Ottawa location was 996 mm and 762 mm for the Scandia location. The average rainfall and temperature at these locations were similar to their respective 30-yr normal values (Table 1). However, there was significant variability in rainfall from year to year at both locations, including extremely dry years like 2012 with approximately half the amount of rainfall compared to the 30-yr average. The Scandia location did receive supplemental irrigation as needed while the Ottawa location was rainfed. Average temperatures were also higher for the 2012 year, likely contributing to significant reductions in corn productivity.

The interaction effect between starter and place-rate was not significant except for 1–2 yr and some crop response variables (Tables 2 and 3). However, for analysis across years, the interaction effect was significant for most crop response variables, particularly at the Scandia location. Discussion of results will focus on the main effects of starter and place-rate for the analysis by year, and the focus on the interaction effect for across-year analysis.

The soil at the Ottawa location is characterized by the presence of a subsoil horizon with an abrupt increase in clay content known as a claypan (Anderson et al., 1990). These soils typically have a relatively low saturated hydraulic conductivity and water-holding capacity. Therefore, this location tend to be more susceptible to frequent drought and flooding conditions (Blanco-Canqui et al., 2002). Results at this location showed a greater uptake of P at the V6 growth stage with deep-band P fertilizer placement at the 39 kg P ha\(^{-1}\) application rate (Fig. 1). Banding fertilizer has been found to increase early growth compared to broadcast (Schwab et al., 2006; Barber, 1980; Mallarino et al., 1999). In Ottawa, V6 whole plant samples were not collected in 2006 or 2010 (Fig. 1).

Phosphorus fertilizer placement as deep-band at the 39 kg P ha\(^{-1}\) application rate also resulted in overall greater ear leaf P concentrations (Fig. 1). However, this trend did not occur for grain P or yield at this location. The control treatment with no P
fertilizer application generally showed the lowest grain P concentration and yield, indicating a response to P fertilizer application. However, the grain P concentration and yield response among the different P fertilizer placement and rate treatments evaluated in this study varied by year, with no clear advantage from one place-rate treatment (Fig. 1). Belcher and Ragland (1972) showed that surface P fertilizer applications were as efficient for corn as a combination of broadcast and banded P fertilizer application. With relatively low corn grain yield (and soybean) at the Ottawa location, the fertilizer application of 39 kg P ha⁻¹ for the 2-yr rotation would be similar to approximate removal values for the corn and soybean at this location (Leikam et al., 2003). Therefore, with the higher P fertilizer application rate it is possible that no response to additional P fertilizer would be expected at this location. The treatments with higher P fertilizer application rate (broadcast and deep-band) generally showed the greatest grain P concentration values (Fig. 1). Previous studies suggest that grain yield is the main driving factor for total P removal. However, a consistently greater grain P concentration with greater P fertilizer application rates will contribute to greater total P removal in the long term.

The main effect of starter fertilizer application generally showed greater P uptake, ear leaf P, and grain P concentration with the application of starter fertilizer at Ottawa for multiple years (Fig. 2). Previous studies have shown the role of starter P and N fertilizer to increase early corn growth and total P uptake.
Results from our study also showed that mid and late season P concentration in the plant (ear leaf P and grain P) are also increased with the use of starter fertilizers (Fig. 2). However, starter fertilizer application did not increase grain yield for most years at the Ottawa location.

In Scandia, whole plant samples at the V6 stage were not collected in 2006, 2009, and 2010. In the years when whole plant samples were collected, greater uptake was observed for deep-band fertilizer application at the 39 kg P ha⁻¹ rate (Fig. 3). However, greater concentrations of P in the plant tissue were observed with the broadcast application at the 39 kg P ha⁻¹ rate (data not shown). The greatest ear leaf grain P concentration was generally found for the broadcast fertilizer application at the 39 kg P ha⁻¹ rate (Fig. 3). The control treatment with no P fertilizer application showed the lowest average crop response parameters (P uptake, ear leaf P, grain P, and yield) showing a response to P fertilizer application. Previous studies suggest that ear leaf P concentrations can correlate with corn grain yield (Stammer and Mallarino, 2018). In Scandia, the highest grain yield was observed with broadcast for the higher fertilizer rates (Fig. 3). Similar to the Ottawa location, the response in early P uptake and ear leaf P did not result in increased yield at the Scandia location (Fig. 1 and 3). Previous studies showed that deep-band applications increased early P uptake compared to broadcast (Schwab et al., 2006). However, greater early P uptake seldom resulted in increased yield as observed in other studies (Barber, 1980; Mallarino et al., 1999).

At the Scandia location, all the measured corn response parameters showed a significant increase with starter fertilizer application across placements and rates. The significance of F values are shown in Tables 3 and 4 and significant main effects (P < 0.1) are indicated by the * symbol.
These results suggest that field conditions of low STP levels and high yielding corn with high P removal (e.g., Scandia location) may benefit from starter fertilizer application more consistently over multiple years. Therefore, under similar STP and corn yield levels, a split-application with at least a fraction of the fertilizer P applied as starter fertilizer with the planter might provide yield benefits when implemented as standard practice by the producer. Previous studies evaluating the use of starter fertilizers in addition to deep-band P fertilizer with the strip-till showed additional plant response to starter fertilizer under some conditions (Adee et al., 2016). This might be related to the increased P availability early in the season with starter fertilizer compared to deep-band that is typically applied about 15 cm below the seed, with a significant effect of P fertilizer placement distance from the corn plants early in the season (Adee et al., 2016).

The two study locations have contrasting environments and therefore productivity potential, the overall average grain yield in Scandia was regularly greater during the 10 yr of the study and with less year-to-year variability than the Ottawa location (Fig. 1 and 3). The average grain yields in 2012 and 2013 were lower than 10-yr average due to a regional drought in addition to high temperatures during critical times for corn growth. Treatment differences at the Scandia location were greater and are likely due to greater yield potential and greater average removal rates with the corn grain yield, exceeding the maximum P fertilizer application rate applied for the 2-yr corn–soybean rotation during this period.

Table 4. Corn response to the main effects of starter (ST) and place-rate (PR), and the interaction of ST × PR average across 10 yr. Corn phosphorus uptake at the V6 growth stage, P concentration in corn ear leaf at the R2 growth stage and grain P after harvest, and grain yield.

<table>
<thead>
<tr>
<th>Main effect</th>
<th>Ottawa</th>
<th>Scandia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P uptake (mg plant⁻¹)</td>
<td>Ear leaf P (g kg⁻¹)</td>
</tr>
<tr>
<td>Control</td>
<td>21.3d</td>
<td>2.49d</td>
</tr>
<tr>
<td>Broadcast, 20 kg ha⁻¹</td>
<td>25.0c</td>
<td>2.79c</td>
</tr>
<tr>
<td>Deep-band, 20 kg ha⁻¹</td>
<td>28.8b</td>
<td>2.95b</td>
</tr>
<tr>
<td>Broadcast, 39 kg ha⁻¹</td>
<td>27.6bc</td>
<td>2.92bc</td>
</tr>
<tr>
<td>Deep-band, 39 kg ha⁻¹</td>
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Starter fertilizer

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<thead>
<tr>
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<th>Ottawa</th>
<th>Scandia</th>
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<tbody>
<tr>
<td>– Starter</td>
<td>25.6b</td>
<td>2.80b</td>
</tr>
<tr>
<td>+ Starter</td>
<td>28.6a</td>
<td>3.02a</td>
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</tbody>
</table>
Averaged over 10-years, the application of starter fertilizer increased corn response parameters (P uptake, ear leaf P, grain P and yield) for the control with no broadcast or deep-band P fertilizer application at both locations (Fig. 5). The P uptake at the V6 stage was also increased by the application of starter fertilizers when P fertilizer was applied broadcast at the total rated of 20 kg P ha⁻¹ (Fig. 5). A significant interaction between the starter and place-rate main effects for P uptake at V6 showed mixed responses to starter fertilizer when P fertilizer was applied via deep-band or a higher rate of 39 kg P ha⁻¹ (Fig. 5). The ear leaf P, gran P, and yield showed similar trends as the V6 P uptake, with significant response to starter fertilizer application for the control and the broadcast P application at the 20 kg P ha⁻¹ (except for ear leaf P at the Scandia location) (Fig. 5).

Grain yield was increased with starter fertilizer application at the Ottawa location only for the control and broadcast P application at the 20 kg P ha⁻¹. Fertilizer treatments with deep-band and higher P application rates showed no yield increase with the application of starter fertilizer at this location. However, at the Scandia location, the highest yield increase from starter fertilizer application was for the control, with smaller and consistent yield increased for P fertilizer place-rate treatment (Fig. 5).

These results showed the impact of site-specific soil, climate, and crop characteristics affecting yield response to the application of starter fertilizers in corn. Is likely that the combination of low STP and higher crop P removal with a higher yield at Scandia contributed to the significant yield increase with the application of starter fertilizer in addition to yield increases achieved with P fertilizer placement and rates.

The main effect of fertilizer place-rate across years showed a significant increase in P uptake, ear leaf P and grain P for the different P fertilizer placement and rates (Table 4). However, yield response was generally similar among the different P fertilizer placement and rates when analyzed across years with significantly lower yield for the control treatment. On the other hand, the main effect of starter fertilizer application showed a significant increase for all the crop parameters evaluated in this study except for grain yield at the Ottawa location (Table 4).

**Changes in Soil Test Phosphorus**

Corn parameters evaluated in this study showed a significant response to fertilizer treatments after multiple years of application (Tables 2 and 3). Soil samples collected after 10 yr generally showed an increase in STP values with the application rate of 39 kg P ha⁻¹ (Fig. 6). The control treatment showed a decrease in STP values with the sampling after 10 yr of cropping. Broadcast (+starter and +starter) application of P fertilizer resulted in a STP increase of approximately 10 mg kg⁻¹ from the starting value with the application of 39 kg P ha⁻¹. With the broadcast application, the changes in STP values were similar for samples collected in-row and between-row with slightly lower STP in-row when no starter fertilizer was applied (Fig. 6). Broadcast fertilizer application provided a uniform distribution of P within the plot, and differences in STP in-row compared to between-row was likely driven by plant P uptake with planting occurring in the same row for 10 yr.

Fertilizer placement with deep-band (+starter and +starter) showed a significant increase in STP for the in-row sampling while values for the between-row samples were similar to the control treatment. Soil test P-value in-row increased by approximately 40 mg kg⁻¹, and showed no change for the between-row samples at both locations for the deep-band P fertilizer placements. These results showed that when P fertilizer is applied as a deep-band at 15–20 cm directly below the row, proper soil sampling becomes especially important as small-scale STP variability can significantly affect results, and therefore fertilizer recommendations. When the same rate of fertilizer was applied, concentrated nutrients in bands with deep-band P fertilizer application can result in areas of increased STP values contributing to high small-scale variability in the field. These results show the potential challenges for soil sampling under long-term
band placement of P fertilizer and the need for revised sampling procedures (Fernández and Schaefer, 2012).

**CONCLUSIONS**

Results from this long-term study demonstrated that P application rate and placement contributed to increased plant growth and P uptake. Grain yield showed a significant increase when part of the total P fertilizer was applied as a starter fertilizer for one location with high yield and P removal in our study (Scandia). On the other hand, the use of starter fertilizers increased grain yield when P fertilizer was applied broadcast at low rates. Furthermore, the increased plant early growth and P uptake from deep-band P fertilizer was not an indicator of greater corn grain yield when compared to broadcast (deep-band vs. broadcast). While grain yield for broadcast and deep-band P fertilizer placement were similar across years, the improved early growth and P uptake from deep-band placement with the strip-till operation may provide benefits at the field scale. Furthermore, results from this study suggest flexibility for P fertilizer placement options for corn production under strip tillage without the risk of yield penalty. For fields managed under different tillage systems. Soil Sci. Soc. Am. J. 70:1099–1109. doi:10.2136/sssaj2011.0352


Mallarino, A. P., J. M. Bordoli, and R. Borges. 1999. Phosphorus and potassium placement effects on early growth and nutrient uptake of no-till corn and relationships with grain yield. doi:10.2134/agronj1 999.000219620910010007x


