Evaluation of long-term phosphorus fertilizer placement, rate, and source, and research in the U.S. Midwest

by

Cristie LeAnne Edwards

B.S., Virginia Polytechnic Institute and State University, 2010
M.S., Virginia Polytechnic Institute and State University, 2013

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
College of Agriculture

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Abstract

The appropriate management for phosphorus (P) fertilizer can have significant agronomic, economic, as well as environmental impact. Studies in Kansas have evaluated different management systems to determine best management practices (BMP). The first component of this dissertation is a comprehensive review of tillage system and P fertilizer placement interaction. This review included studies completed in the U.S. Midwest. Results of this review showed greater corn yields with conventional tillage and broadcast applications when soil test P levels (STP) were below 20 mg P kg^{-1}. However, soybean yield was highest in no-till systems with broadcast P fertilizer applications.

The second component if this dissertation was a long-term study conducted in Kansas to evaluate the effect of P fertilizer placement on corn and soybean production. Results showed that under strip-tillage, P fertilizer placement significantly affected corn growth, but, seldom resulted in yield response difference among placement methods. Phosphorus application as starter fertilizer at planting showed the most consistent yield response. In addition to the agronomic aspect of this study, the third component of this dissertation consisted of an economic analysis using partial budgets calculated using both fixed and varying prices and costs to compare management practices. With decreased application costs associated with deep banding in strip-tillage system, net returns are greater than broadcast applications. The highest net responses were observed with starter P fertilizer applications.

The fourth component of this dissertation included a study evaluating the effects of chelated fertilizer on nutrients, such as P, Fe, Mn, and Zn in soybean. Results from our study showed that both ethylenediamine tetraacetic acid (EDTA)+P and hydroxyethyl ethylenediamine tetraacetic acid (HEDTA)+P resulted in greater concentrations and uptake of Fe and lower Mn

uptake in soybean. However, the application of glucoheptonate (GCH)+P had no negative effect on Mn uptake compared to EDTA+P and HEDTA+P. Across locations, EDTA+P and HEDTA+P showed higher yield than GCH+P.

The use of long-term studies and comprehensive reviews can provide a unique perspective and better understanding of the most appropriate BMPs for P fertilizer management. Many agronomic and environmental implications of P fertilizer management and the interactions with tillage systems and soils may only become noticeable after multiple years or in a variety of conditions.

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The author would like to dedicate this original thesis to her entire family, without their encouragement, this milestone would not have been possible. Her family has shown her that anything is possible with hard work, dedication, and a loving family.

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Chapter 1 - Introduction

When analyzing different management systems, three main components should be considered; (1) agronomic impact on crop yields, (2) economic return, and (3) environmental impact. No one management practice will satisfy all components. However, by conducting research or combining data from multiple sources, treatment effects on yield can be made on individual studies or over differing environmental conditions. Phosphorus (P) placement and interactions with tillage have been extensively studied for corn and soybean production in the US. Various tillage systems ranging from no-tillage to minimal tillage to conventional tillage are utilized in these production systems. Placements can consist of broadcast, surface and subsurface banding, and can either use dry or liquid products. By combining data from various publications with similar treatments, a quantitative systematic review can be conducted. Thus, an overall response to tillage system, placement, or tillage system by placement interaction can be estimated within specific environmental conditions or parameters. However, this review process does have its limitations and inferences can be made based only based on the geographic region and soil conditions included in the review. Therefore, there is still a need for independent studies to evaluate placement and tillage under specific environmental and soil conditions.

There is increasing interest in minimal tillage systems. Particularly, strip-tillage combines the benefits of both conventional and no-tillage systems and allows for deep banding of fertilizer directly below the plant. Previous studies have shown similar yields with deep banding and broadcast fertilizer placement. However, with deep band applications in the same pass as tillage, fertilizer application costs would be reduced and therefore, there would be greater chance of higher net returns. On the other hand, some long-term studies evaluating P fertilizer placement have shown higher corn yields with broadcast applications. There is a lack of data evaluating the long-term effects of P fertilizer placement under minimal tillage systems. There is even less data available evaluating long-term effects on all three components of agronomic, economic return, and environmental impacts.

To maximize profits, the interest on products and sources to increase P fertilizer efficiency have risen over the years. Previous research has shown that chelated fertilizers can have a positive effect on P fertilizer availability. However, these findings have been primarily in a laboratory settings (Edwards et al., 2016a) or greenhouse settings (Edwards et al., 2016b). It is unclear what effects these products might have on other nutrients and under field production conditions. Thus, there is a need for additional research in a field setting under various soil and environmental conditions.

Dissertation Organization

This dissertation is presented in four chapters that are preceded by a general introduction and proceeded by general conclusions (Chapters 1 and 6). The titles of the chapters are: “Corn and soybean response to phosphorus fertilizer placement and tillage interaction in the US Midwest: A Review” (Chapter 2); “Corn response to long-term phosphorus application rate and placement under strip-tillage” (Chapter 3), “Economic evaluation of long-term phosphorus placement in a corn-soybean rotation under strip-tillage” (Chapter 4) and “Evaluating the interaction between chelated Fe fertilizer sources and placement on soybean” (Chapter 5). Each chapter includes an abstract, introduction, materials and methods, results and discussion, conclusions, and references.

Chapter 2 includes a review of published research and review of fertilizer placement and tillage interactions in the Midwest. This review is merely the combination of data from individual independent studies with the purpose of integrating the findings. Data were analyzed for comparison of broadcast and banding placements in conventional tillage and no-tillage systems. Specific criteria was set to search common databases containing agriculture journals to attempt to avoid publication bias. Variables analyzed included corn and soybean yields. The increase practice of reviews in agriculture has proven useful in analyzing similar studies in various environmental conditions.

A study evaluating the long-term effects of P placement in strip-tillage systems is the main focus of Chapter 3. This project was initiated in fall of 2005 at 4 locations across Kansas. However, only corn data for the Republic and Franklin counties were addressed in this dissertation and soybean data are included in the Appendix. This study has value for long-term evaluation of P fertilizer placement. Short term studies are limited in the amount of inference. Long-term studies allow for the evaluation of placement effects on soil test phosphorus levels as P fertilizer application has found to have residual effects on future crops.

A partial budget was constructed for an economic analysis of net return for each management system using fertilizer inputs, application and equipment costs, and grain prices (Chapter 4). With application of fertilizer in a deep band with strip-tillage, additional costs associated with broadcast applications may not be economical. The long-term study described in Chapter 3 was used to determine if long-term P fertilizer placements of broadcast, deep band, or combinations of different placements result in greater net return.

Previous research had indicated that EDTA and HEDTA can increase plant available P with applied to soil. A study evaluating P availability with the application of chelated fertilizer at the field level was conducted in 2014 and 2015 (Chapter 5). For this study, 6 site years of soybean were included with locations in Republic Co and Shawnee Co in 2014 and 2015, Reno Co in 2014, and Thomas Co in 2015. Treatments included a control and a factorial of two placements (in-furrow and surface band) and four fertilizers (P only, EDTA, HEDTA, and Glucoheptonate). EDTA and HEDTA are common acid-based chelated iron sources and the glucoheptonate is a new sugar-based chelated iron source. Results show no yield differences or phosphorus uptake. The well documented antagonistic effect of chelated-iron sources on manganese uptake in soybean was observed with EDTA and HEDTA application, but not with the glucoheptonate.

With increasing P fertilizer price and more emphasis on environmental concerns, best management practices (BMP) need to be determined for a particular situation. These studies focused on practices under field conditions and that are applicable to producers to answer problems they face with P management to improve plant availability and profitability while minimizing environmental impact.

Chapter 2 - Corn and soybean response to phosphorus fertilizer placement and tillage interaction in the US Midwest: A Review

ABSTRACT

Phosphorus (P) placement and tillage system interactions have been extensively studied for corn (*Zea mays* L.) and soybean (*Glycine max* L.) production in the U.S. Midwest. The objective of this study was to evaluate the effects of phosphorus (P) fertilizer placement and tillage system interactions on corn and soybean yield. A review was conducted including publications from 1980 to 2016 with studies in the Midwest region. Treatments included two tillage systems (conventional and no-till) and two placements (broadcast and band). Five common databases were searched with standard keywords across all databases. Coding criteria were set to include site identification, soil test P levels, tillage system, fertilizer P rate and placement, and statistical information. Data was analyzed using direct evidence, comparing means within study as response ratios, and all evidence, comparing means between studies, for tillage system and placement effects on corn and soybean yield. Results of all evidence analysis show higher corn yield means with broadcast applications in soils with soil test P (STP) below <20 mg P kg^{-1}. Higher corn yields were also observed with conventional tillage in soils with high STP. Analysis of direct evidence shows generally lower corn yields in no-till systems with little difference between placements. This is potentially due to study locations in the upper Midwest like in Iowa and Illinois. However, soybean yields were higher in no-till systems and showed higher response to broadcast applications in high STP. Band P fertilizer applications yielded highest in high STP and may provide a yield increase only if the rates are limiting (<20 kg P ha^{-1}). Perhaps the largest overall benefit to P placement may come from reduction in runoff.

Keywords: tillage, no-till, phosphorus, fertilizer placement, corn, soybean, review

INTRODUCTION

Phosphorus placement and interactions with tillage system has been evaluated extensively for corn and soybean in the US. However, research has shown differing results based on geographical area. In the northern Midwest, conventional tillage systems yielded higher compared to no-tillage systems (Bermudez and Mallarino, 2001; Bordoli and Mallarino, 1998). In areas where moisture may be limiting, no-tillage practices conserve water and therefore, can increase yields. Results suggest that placement of P fertilizer can play an important role in early P plant uptake and yield as well as potential P losses to surface water for some soils and tillage conditions. The rate of P uptake per unit of root in corn decreases throughout the vegetative growth phase (Mengel and Barber, 1974), and therefore early season P fertilizer applications and placement can be particularly important for optimum plant growth. Therefore, by combining data from multiple sources, general trends in effects of P fertilizer placement and tillage system interaction can be determined.

Broadcast application can result in a more uniform distribution and fertilizing more soil volume. However, accumulation of P near the soil surface may result in increased lost potential with runoff. Increasing the soil-fertilizer ratio also can potentially decrease P availability in soils with high P sorption capacity. Therefore, using concentrated bands and placing fertilizer near the plant may improve plant-available P in some management systems. Broadcast application may be more practical for some producers and suitable for some soils and tillage conditions. Soil and tillage conditions and the interaction with P application methods should be evaluated with larger datasets and across different soils and environments.

Accurate evaluation of tillage system and placement interactions would require large dataset that comprise a variety of soils, tillage systems and placement combinations. A meta-analysis is a quantitative systematic review of published/non-published literature following sound methods and quality control of data (Philibert et al., 2012; Wang and Bushman, 1999). When there is not enough statistical information published with means, a true meta-analysis cannot be completed, and a review may be a potential alternative (Doré et al., 2011). A key component of a good review includes comparisons of studies with similar components. Several authors have included the following list of components, which can be used for gathering data for a review: (1) correct description of the bibliographic search procedures; (2) listing of the references of the selected individual studies used; (3) analysis of the variability of the results of individual studies, including estimation of variability between the selected individual studies, and, when relevant, investigation of the sources of between-study variability; (4) analysis of the sensitivity of the conclusions to any change in the dataset and/or in the statistical method used to analyze the data; (5) assessment of the publication bias; (6) data weighting, when the results reported in the individual studies differ in their levels of accuracy; (7) availability of the dataset; and (8) availability of the program used for statistical analysis (Borenstein et al., 2011; Gates, 2002; Roberts et al., 2006; Sutton et al., 2000; Wang and Bushman, 1999). However, many published reviews do not follow such procedures and therefore adequate comparisons of treatments are questionable. By doing a wider search of “gray” or unpublished data in non-peer reviewed sources, publication bias can be avoided. However, grey data were not included in this paper.

Within a database, data can be examined in multiple ways. Data can be analyzed as direct evidence using response ratios, where all treatments are present in one study for comparison. However, when little or no data directly comparing two treatments is available, indirect evidence or comparisons can be used (Bucher et al., 1997). This analysis could include any study with partial combination of treatments. Direct comparisons should be used when possible. In an indirect evidence analysis, there is no way of evaluating the magnitude of treatment effects across studies, and therefore affecting inferences made on the dataset (Bucher et al., 1997). The objectives of this study were to evaluate the effects of P fertilizer placement, tillage system, and the interaction on (i) corn and soybean yield means from all published evidence and (ii) corn and soybean response ratios in studies with direct comparisons.

MATERIALS AND METHODS

Search criteria

This review was developed using the steps described by Philibert et al., 2012, and with special attention to the quality of the review procedure. A database search for all publications that included yield data for corn and soybean was conducted within Wiley International Science, Springer Link, Web of Science, Science Direct, and ACSESS Digital Library databases. The primary search criteria were set to include publications from 1980 to 2016 and studies conducted in the Midwest or Great Plains region of the US (Colorado, Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Montana, Nebraska, North Dakota, Ohio, Oklahoma, South Dakota, and Wisconsin). References published after 1980 with individual studies with dates prior to 1980 were included in the analysis. Publications from these databases were categorized as “peer-reviewed”.

Published articles were selected based on key criteria for quality of information and relevance. Coding parameters were set to include publication information (given a specific identification number), site information (location, state, and study year), background soil (soil series, classification, soil test method, soil sampling depth, STP, and soil test potassium), management practice (tillage system type, P fertilizer rate, P application method, and P source), crop information (corn hybrid, soybean cultivar, crop yield means), and statistics (number of replications, standard error (SE), coefficient of variation (CV), and p-values). Publications were first categorized as peer reviewed and non-peer reviewed. Soil test P levels were categorized as “low” (<20 mg kg^{-1}) and “high” (>20 mg kg^{-1}). In the Midwest, critical levels for corn production can range from 15 to 25 mg kg^{-1} (Liekam et al., 2003; Vitosh et al., 1995; Mallarino et al., 2013), therefore 20 mg kg^{-1} was used in this study.

Means for comparing tillage system and placements were combined for the analysis as a factorial of two tillage systems (conventional and no-till) and two placements (broadcast and band). Tillage systems were categorized into conventional tillage (CT) and no-till (NT). Papers including chisel, chisel+disk, conventional, coulter, cultivate, disk, incorporated, moldboard, ridge tillage, strip-tillage, and zone-tillage were considered conventional tillage for this review. There was no condition established on the number of years field were under no-tillage systems, and therefore the studies included in this review varied on the number of years under no-tillage. Only P fertilizer rates of above 20 kg P ha^{-1} and below 80 kg P ha^{-1} were included in the analysis. At these rates, starter application rates were not included and rates were close to removal rates. Fertilizer placement of deep band, in-furrow, 5 cm by 5 cm, surface band, dribble band, knife, and injected liquid and dry fertilizer were considered “band”. Both liquid and dry fertilizer applications made to the soil surface as uniform application were considered “broadcast”. Combination or split applications of broadcast and banding were not included in this study. Only data from studies where soybeans were fertilized were included in this study. As with corn, only P fertilizer rates applied to soybean above 20 kg P ha^{-1} and below 80 kg P ha^{-1} were included in this analysis. Phosphorus fertilizer application methods were categorized the same as corn into broadcast and band applications. Double cropped soybeans were not included in the analysis, only full season soybean crop. Studies involving manure applications that contained an inorganic fertilizer were included in this database.

Statistical analysis

Data were analyzed using two methods for corn and soybean yield means: all evidence and direct evidence. All evidence analysis included studies with any combination of conventional tillage and no-till comparisons or the comparison of broadcast and band placement, as described above. All evidence corn and soybean yield means were analyzed using *proc Glimmix* in SAS 9.4 (SAS Institute, 2015) by STP levels above and below 20 mg P kg^{-1}. Individual studies (site-years) within publications were used as random variables for all evidence analysis. When the tillage system and placement interaction was significant, main effect test were ignored and main effect tests were tested between tillage system and P fertilizer placement within each STP level. If the interaction was not significant, the statistical significance of main effects were determined ($p<0.10$).

There was not enough data to determine the main effects of tillage system or placement or the interaction on corn or soybean yield. Therefore, the direct evidence analysis consisted of studies with treatments comparing either one tillage system (conventional or no-till) with both P fertilizer placements (broadcast and deep band) or either one of the P fertilizer placements (broadcast or band) with both tillage systems (conventional and no-till). Thus, allowing for the direct comparison of either tillage system or placement on corn and soybean yield means. Response ratios for the main effect of tillage system ((no-till – conventional tillage)/conventional tillage)x100 and placement ((broadcast - band)/band)x100 were calculated using yield means. Corn yield responses to broadcast ((broadcast – band)/band)x100 within conventional and no-till systems were also calculated. Data were analyzed using *proc Glimmix* in SAS 9.4 (SAS

Institute, 2015) by STP levels above and below 20 mg P kg-1. Individual studies (site-years) within publications were used as random variables in the direct evidence analysis.

RESULTS AND DISCUSSION

Search criteria

Table 2.1 show the flow of publications that were considered for acceptance into this database and the reasons why they were excluded. These publications were found within the ACESS Digital Library database. There was a total of 21,256 corn yield observations considered for all data analysis that were condensed to 3,121 in 34 publications due to non-peer reviewed publications and no yield, STP, tillage system, placement, and rate (Table 2.1). In recent years, several review papers have summarized “unpublished” datasets, showing the value of this information with proper assessment of the quality of the data (Tremblay et al., 2012). However, the use of only peer-reviewed publications may provide additional assurance regarding the quality of the studies and the data included. For the direct data analysis, 499 corn yield observations in 8 publications were used after observations were excluded due to lack of tillage system or placement comparison in 26 publications. Table 2.2 gives each publication used in all evidence and direct evidence analysis, states where studies were conducted, the number of studies or site years within the publications, the number of yield observations, and within which STP category each publication was analyzed. Even though all states in the Midwest were considered for this review, the data here is heavily influenced by the northern Midwest states, particularly Iowa (Table 2.2). Specifically, in the direct analysis of corn yield means, majority of the data arise from Iowa, Illinois, and Minnesota. Due to geographical location, no-till systems tend to yield higher (Bermudez and Mallarino, 2001; Bordoli and Mallarino, 1998; Fernandez and Schaefer, 2011). However, in areas such as Kansas, conventional tillage systems have yielded higher (Schwab et al., 2006).

The soybean database was built using the same criteria as for corn yield. For soybean yield, a total of 10,086 observations in 52 publications were considered for analysis before data were excluded for being non-peer reviewed and for not including yield, STP, tillage system, placement, or rate. Soybean data were further reduced to where only fertilized studies were included. Therefore, no residual studies were included in this analysis. The result was 741 yield observations in 11 publications. For direct analysis of soybean yields, observations were excluded for lack of tillage system and placement comparison, and therefore 284 observations in two publications were considered for analysis (Table 2.1). However, there was not enough data for calculating response ratios for direct analysis of soybean yield in either low STP (<20 mg kg^{-1}) or high STP (>20 mg kg^{-1}). The publications used in analysis are listed in Table 2.3. As with the corn yield means available, P fertilizer placement and tillage system studies mainly originated in Iowa (Table 2.3). This can heavily influence the inference made on data available. However, by setting strict criteria and following it, areas where little research has been conducted on placement and tillage system can be determined.

Studies from a total of 11 states met the selection criteria and were included (Colorado, Illinois, Indiana, Iowa, Kansas, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin); and seven states did not meet the criteria (Colorado, Michigan, Missouri, Montana, North Dakota, Ohio, and Oklahoma) for corn yields (Table 2.2). Only Iowa, Minnesota, Illinois, and South Dakota had studies with all evidence analysis for soybean yields (Table 2.3). Studies from Illinois, Iowa, Kansas, and Minnesota allowed for direct evidence of tillage system and P placement effects on corn yield. The dataset developed with this search was analyzed using different categories. For the tillage system category, the studies were categorized in two categories: no-till and conventional tillage. The conventional tillage included strip-till and minimum tillage systems. Phosphorus placement categories were defined as broadcast and band; the band category included different types of subsurface and surface band placement, and data shown here only include fertilizer rates with 20 kg P ha^{-1} or more.

Corn yield

Table 2.4 shows the significance of the main effects for tillage system, placement, and interaction on corn and soybean yield means using all evidence analysis of means. A significant main effect of placement was found on corn yield when STP levels were below 20 mg P kg^{-1}. Broadcast applications, regardless of tillage system, were found to have higher yield means than banding P fertilizer (Figure 2.1). There were no differences in tillage systems with low STP. However, when STP levels were above 20 mg P kg^{-1}, conventional tillage resulted in higher yields compared to no-tillage with no differences in placement (Figure 2.2). The number of observations with conventional tillage (827) could lead to higher means due to a greater sampling pool compared to no-till (166).

The response ratio of tillage systems showed lower corn yields with no-till using direct evidence (Figure 2.3). These results agree with previous studies, and no-till systems seem to provide relatively higher yields under arid conditions. This could potentially be attributed to soils having higher water holding capacity in the study areas. Previous studies have shown that yields can be lower under humid conditions in no-till systems, such as the area for this study in the U.S.A. (Brouder and Gomez-Macpherson, 2014; Pittelkow et al., 2015a; Pittelkow et al., 2015b). However, it is also possible that the current body of literature comparing no-till versus conventional tillage is not providing a fair evaluation of both tillage systems. Some researchers suggest that a no-till system is comprised of many factors that are essential for no-till, and only production in the absence of tillage cannot be considered no-till system (Derpsch et al., 2014). This may require some revision of the methodology used for current tillage system research in general.

Corn yield response to broadcast P fertilizer application showed lower yields when compared to banding application when STP were above 20 mg P kg^{-1}. However, there were no significant advantages when STP was below 20 mg P kg^{-1} (Figure 2.3). Broadcast applications were only higher than banding with conventional tillage with low STP (Figure 2.4).

It is important to emphasize that this analysis was completed for phosphorus application rates above 20 kg P ha^{-1}. It is possible that lower fertilizer application rates would show higher efficiency (higher yields) with band application compared to broadcast applications, especially with STP levels that are high in both conventional and no-till systems (Figure 2.4). These results may require additional evaluations to see if confounding factors such as fertilizer application rates are not affecting these values, thus creating a possible bias in the results. In this study, upper application rates were set at 80 kg P ha^{-1}. There were little differences in placement in no-till systems with low and high STP (Figure 2.4). However, these response ratios were calculated from one publication in soils with low STP in no tillage systems (Schwab et al., 2006). Studies with high STP and no-tillage were limited to two studies (Fernandez and White, 2012; Fernandez and Schaefer, 2003) and the same for conventional tillage systems (Fernandez and Schaefer, 2003; Bordoli and Mallarino, 1998).

Soybean yield

In the Midwest, soybean are usually planted without prior tillage following corn production. Extensive research has shown higher soybean yields in no-till systems (Yin and Al-Kaisi, 2004). When looking at all evidence data available, tillage system affected soybean yield means at any STP level (Table 2.4). No-till soybean production in soils with low STP resulted in higher yield means compared to conventional tillage (Figure 2.5). However, there may be discrepancies in determining how many years of no-till or if corn received some type of tillage and soybean was planted no-till. Prolonged use of no-till has been found to increase soybean yield, but this decreases corn yields compared to conventional tillage (Randall et al., 1996).

In studies with high STP, there was a significant interaction between tillage system and P fertilizer placement (Table 2.4). Systems with no-till and broadcast applications resulted in higher soybean yields compared to banding in these high STP soils (Figure 2.6). No matter the fertilizer placement, no-till systems still resulted in higher soybean yield (Borges and Mallarino, 2001; Buah et al., 2000). This result could be attributed to increased organic matter in no-tillage systems. A different geographical region with different soils and environment may generate different results. A study in Mississippi showed no-till soybeans responded more to band applications than to broadcast applications (Hairston et al. 1990). Research has also shown that soybeans respond more to being fertilized as opposed to residual effects from corn applications in the rotation. Therefore, further research is needed to examine the residual effects of placement and tillage systems have on soybean production.

Both Illinois and Iowa did have publications with studies that compared either multiple tillage systems or multiple P fertilizer placements on soybean production (Farmaha et al., 2011;

Mallarino and Borges, 2000) (Table 2.3). However, there was not enough data to directly compare tillage system or placement.

CONCLUSION

The literature search completed for this study revealed many issues related to data presentation/availability in peer-reviewed papers, including differences and inconsistences among journals and papers within journals (i.e., background soil information, soil sampling methods and limited detail on fertilizer sources used). There was also a lack of statistical data available with published means. Therefore, variation within a study could not be determined. However, data were analyzed for all evidence and direct evidence for tillage system and P placement effects on corn and soybean yield. When STP levels were below critical levels, broadcast applications resulted in higher corn yields compared to banding fertilizer application. There were no differences in placement when STP levels were above critical levels, but there was a response to conventional tillage. Studies consisting of direct evidence showed higher corn yield with broadcast applications in low STP. However, when STP were above critical levels, corn yields were lower with broadcast applications compared to banding in both conventional and no-tillage systems. As for soybean yield, no-tillage systems yielded higher in studies with both below and above critical level for STP. Only when STP levels were above 20 mg kg^{-1} was there an interaction between P fertilizer placement and tillage system. Soybean yield was highest in no-tillage systems with broadcast applications. There were only two publications with direct comparisons of tillage system and P fertilizer placement; therefore, not enough data was available. Based on this review and the area searched, producers could maximize yields of a corn-soybean rotation with some type of tillage performed before corn, and with soybean planted with no-tillage. Both crops should be fertilized using broadcast P fertilizer applications when

STP levels are below critical levels. The geographical area of the data analyzed in this study, particularly in the direct evidence, needs to be considered when evaluating management practices.

Future improvements in data stewardship are clearly needed to increase access and improve the use of published data on this topic. It is our recommendation that publications include, but not limited to, background soil test information, tillage system used, fertilizer application rates, and fertilizer application methods. Additional statistical data including treatment effects (p-values), standard error, standard deviation, or CV should also be included. This would allow for analyzing data and making inference in future analysis, such as Meta-analysis.

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Table 2. 1. Flow of study selection including number of publications considered and the selection criteria.

Category	Reason†	Corn	Soybean
	<u>All evidence</u>		
Potentially relevant publications		110	52
Excluded	No STP included in the publication	3	8
	Tillage system information was not provided	6	2
	No P rate information	51	12
	P placement method information was not included	9	6
	No Yield reported	7	2
	Corn residual applications	---‡	11
Included		34	11
	<u>Direct evidence</u>		
Excluded	No Tillage system /Placement comparison	26	9
Included		8	2

† STP, soil test phosphorus.

‡ Corn yield means with no P applied were not included in analysis. Soybean yield means for both fertilized and residual were included in the databased, but only fertilized soybeans were included in analysis.

Table 2. 2. Characteristic of studies included in the all evidence and direct evidence analysis for tillage system and phosphorus placement interaction on corn yield. †

Reference	State	Studies‡	Observations‡	STP§
	All evidence			
Al-Kaisi and Kwaw-Mensah, 2007	Iowa	3	36	high
Barbazan et al., 2008	Iowa	9	36	high, low
Bermudez and Mallarino, 2001	Iowa	1	8	high
Bermudez and Mallarino, 2002	Iowa	1	1	high
Bermudez and Mallarino, 2007	Iowa	1	12	high, low
Bordoli and Mallarino, 1998	Iowa	26	170	high, low
Borges and Mallarino, 2001	Iowa	15	60	high, low
Coulter et al., 2011	Minnesota	16	96	low
Fernandez and Schaefer, 2011	Illinois	2	108	high
Fernandez and White, 2012	Illinois	3	45	high
Ginting et al., 1998	Minnesota	1	2	low
Gordon et al., 1997	Kansas	3	60	high
Kaiser et al., 2005	Iowa	16	48	high, low
Mallarino et al., 2011	Iowa	6	18	high, low
Mallarino et al., 2008	Iowa	10	80	high, low
Mallarino et al., 1991b	Iowa	11	198	high
Mallarino, 1996	Iowa	25	75	high, low
Mallarino and Blackmer, 1992	Iowa	25	150	high, low
Mallarino, 1995	Iowa	41	106	high, low
Osborne et al., 2002	Nebraska	2	48	low
Paschold et al., 2008	Nebraska	2	2	low
Randall et al., 2001	Minnesota	8	104	low
Riedell et al., 2000	South Dakota	3	12	low
Ruan et al., 1987	Nebraska	6	612	low
Schlegel et al., 1996	Kansas	30	180	low
Schwab et al., 2006	Kentucky	3	36	low
Sneller and Laboski, 2009	Wisconsin	3	12	low
Sweeney et al., 2008	Kansas	3	72	low
Tarkalson and Bjorneberg, 2013	Idaho	4	40	low
Tarkalson and Bjorneberg, 2010	Indiana	4	20	high, low
Vetsch et al., 2007	Minnesota	3	392	high
Webb et al., 1992	Iowa	14	168	high, low
Wittry and Mallarino, 2004	Iowa	6	6	low
Wortmann et al., 2009	Nebraska	34	102	high, low
Wortmann et al., 2011	Nebraska	3	6	high
	Direct evidence			
Al-Kaisi and Kwaw-Mensah, 2007	Iowa	3	36	high
Bermudez and Mallarino, 2001	Iowa	1	8	high
Bordoli and Mallarino, 1998	Iowa	15	90	high, low
Fernandez and Schaefer, 2011	Illinois	2	108	high
Fernandez and White, 2012	Illinois	3	45	high
Randall et al., 2001	Minnesota	8	104	low
Schwab et al., 2006	Kentucky	3	36	low
Sweeney et al., 2008	Kansas	3	72	low

† All evidence analysis consists of all studies with any treatment of tillage system or placement and direct comparison analysis with treatments comparing tillage system and placement.

‡ Study observations are site years within each publication and Obs, are the individual treatment quantity within each publication.

§ STP, soil test phosphorus category defined in the analysis of studies as low (<20 mg kg^{-1}) and high (>20 mg kg^{-1}).

Table 2. 3. Characteristic of studies included in the all evidence and direct evidence analysis for tillage system and phosphorus placement effects on soybean yield. †

Reference	State	Studies‡	Observations‡	STP§
	All evidence			
Barbazan et al., 2008	Iowa	7	14	high, low
Bermudez and Mallarino, 2007	Iowa	5	5	high, low
Borges and Mallarino, 2003	Iowa	7	28	high, low
Coulter et al., 2011	Minnesota	16	48	low
Farmaha et al., 2011	Illinois	3	216	high
Mallarino and Borges, 2000	Iowa	25	70	high, low
Mallarino et al., 2008	Iowa	10	80	high, low
Mallarino and Borges, 2005	Iowa	7	14	high, low
Mallarino et al., 1991b	Iowa	11	198	high
Polito et al., 2000	Iowa	8	64	high, low
Riedell et al., 2013	South Dakota	1	4	low
	Direct evidence			
Farmaha et al., 2011	Illinois	3	216	high
Mallarino and Borges, 2000	Iowa	24	68	high, low

† All evidence analysis consists of all studies with any treatment of tillage system or placement and direct comparison analysis with treatments comparing tillage system and placement.

‡ Study observations are site years within each publication, and observations, are the individual treatment quantity within each publication.

§ STP, soil test phosphorus category defined in the analysis of studies as low <20 mg kg^{-1} and high >20 mg kg^{-1}.

Table 2. 4. Significance of F values for tillage system, placement, and interaction on corn and soybean yield means using all evidence analysis.

STP level†	Tillage system (T)	Placement (P)	T × P
	- - - - - - - - - - - - - -	p > F - - - - - - - - - - - - - - - -	
		Corn	
Low	0.798	0.001	0.651
High	0.004	0.856	0.404
		Soybean	
Low	0.048	0.870	0.873
High	0.001	0.027	0.099

† STP, soil test phosphorus defined as low (<20 mg kg^{-1}) and high (>20 mg kg^{-1}).

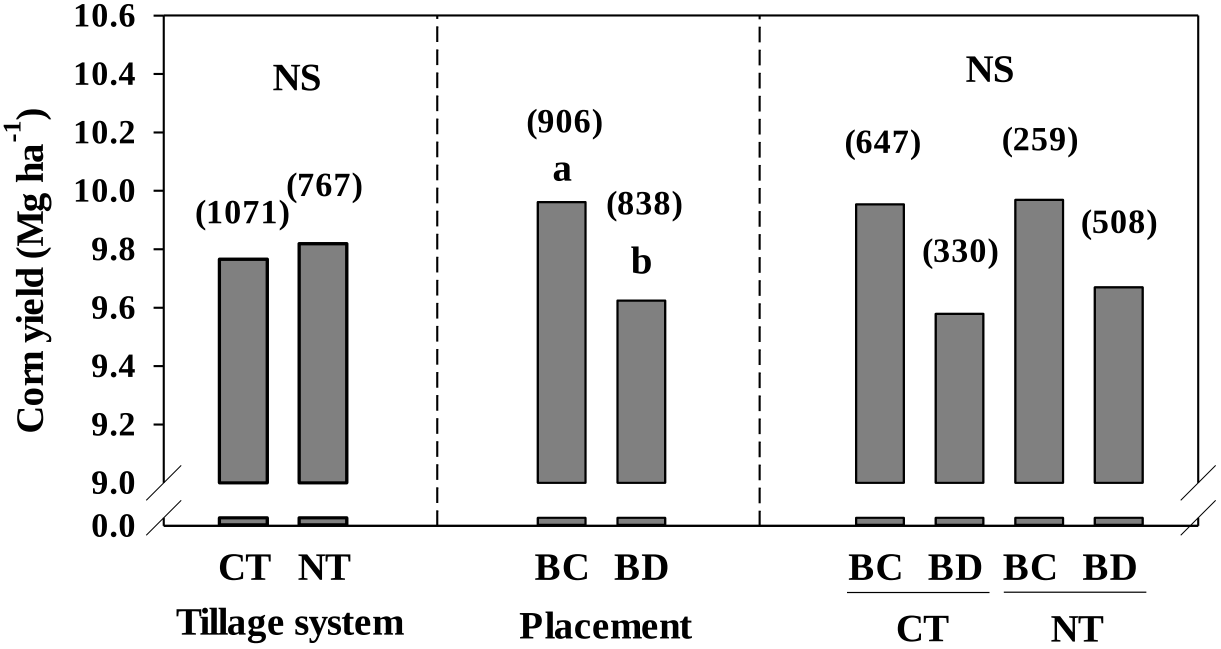

Figure 2. 1. All evidence comparison of main effects of tillage system (CT, conventional tillage and NT, no-till) and placement (BC, broadcast and BD, band) and the interaction on corn yield in soils with low (<20 mg kg^{-1}) soil test phosphorus (STP). Different letters show significance (*p<0.10)* and NS, non-significant means. Numbers listed in parenthesis are the total corn yield mean observations used in the analysis.

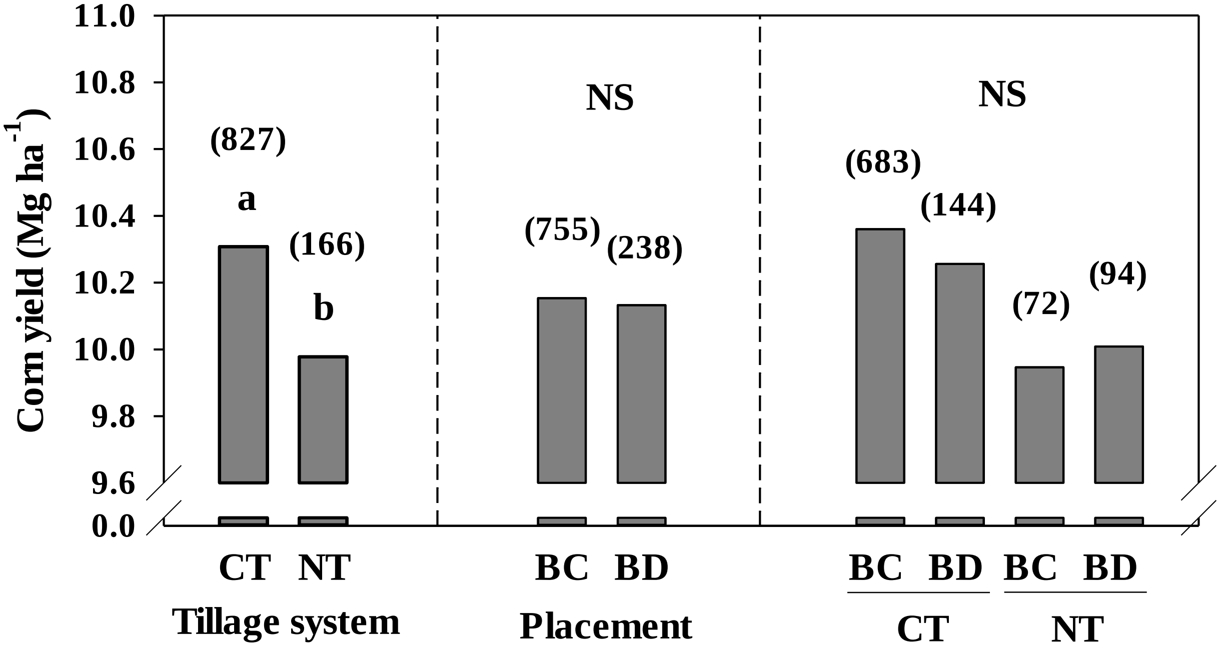

Figure 2. 2. All evidence comparison of main effects of tillage system (CT, conventional tillage and NT, no-till) and placement (BC, broadcast and BD, band) and the interaction on corn yield in soils with high (>20 mg kg^{-1}) soil test phosphorus (STP). Different letters show significance (*p<0.10)* and NS, non-significant means. Numbers listed in parenthesis are the total corn yield mean observations used in the analysis.

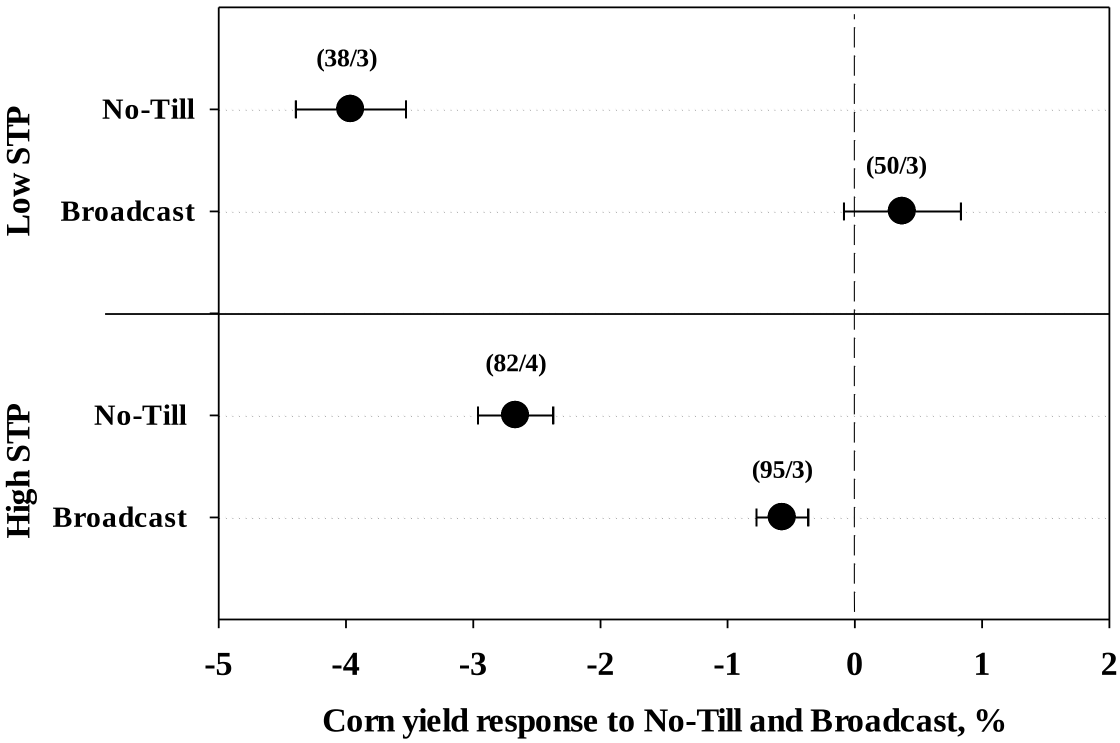

Figure 2. 3. Response ratio for the effect of tillage system and phosphorus (P) placement using direct evidence of corn yield response to tillage system ((No till-conventional)/conventional)*100 and P placement ((broadcast-band)/band)*100 with low (<20 mg kg^{-1}) and high (>20 mg kg^{-1}) soil test phosphorus (STP). Numbers listed in parenthesis are yield mean observations included/number of publications. Bars signify standard error.

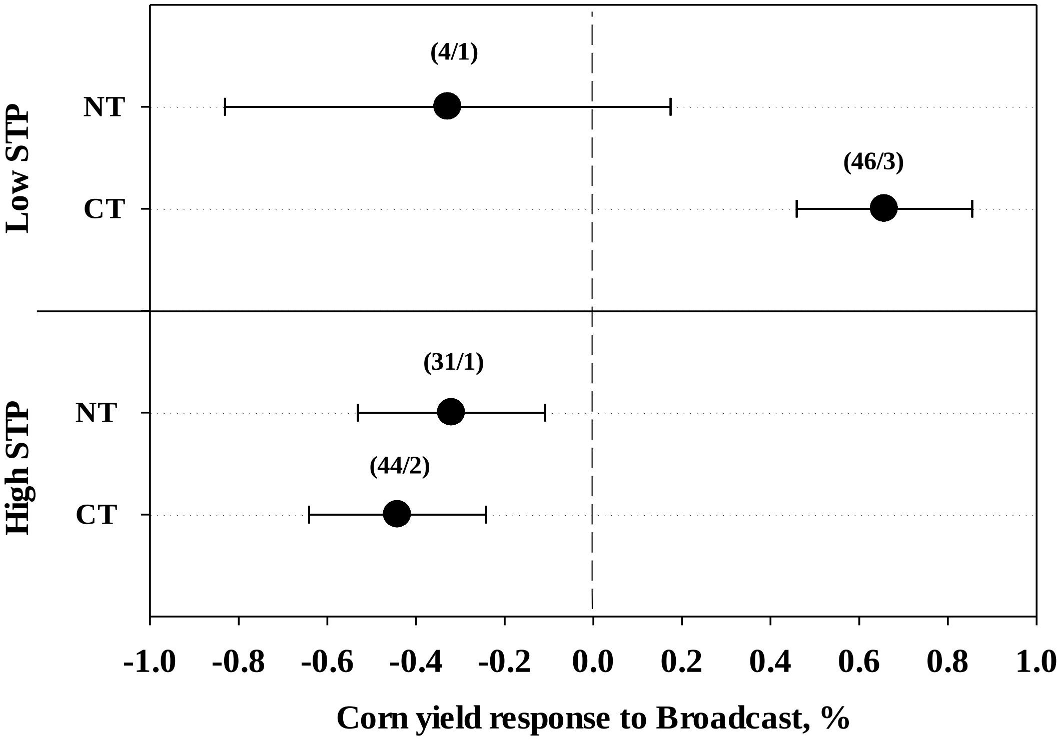

Figure 2. 4. Response ratio for the effect of phosphorus (P) placement under different tillage systems using direct evidence of corn yield response ratios ((broadcast-band)/band)*100 within Conventional Tillage system (CT) and No-Till (NT) in studies with low (<20 mg kg^{-1}) and high (>20 mg kg^{-1}) soil test phosphorus (STP) level. Numbers listed in parenthesis are yield mean observations included/number of publications. Bars signify standard error.

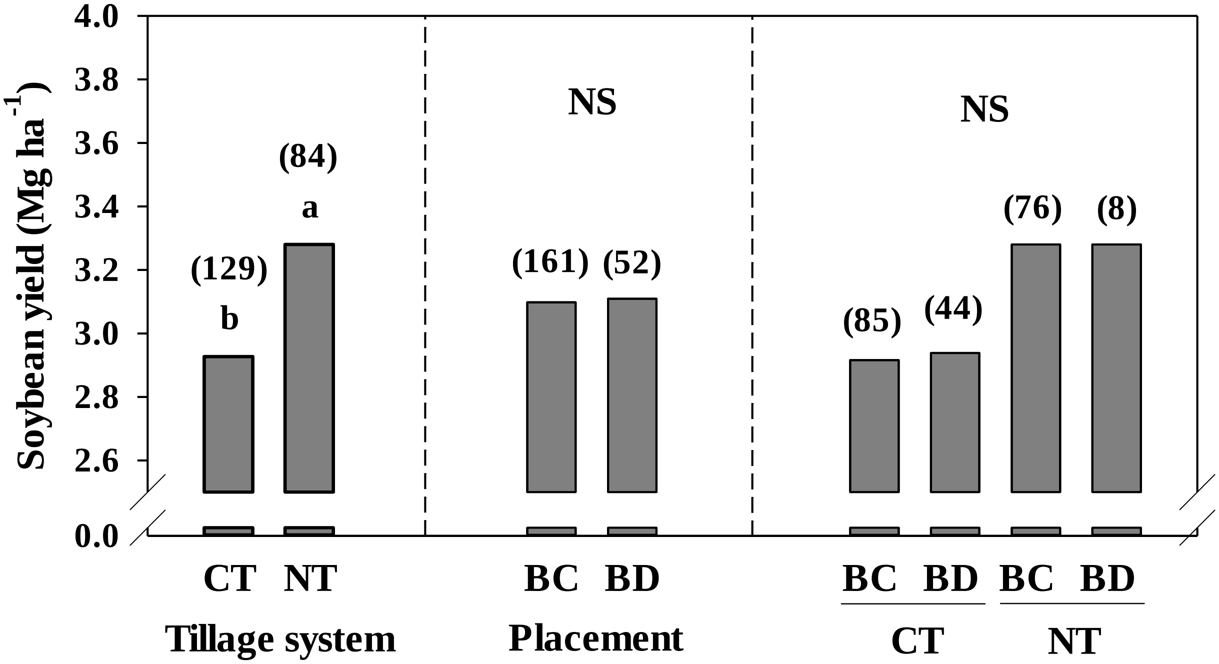

Figure 2. 5. All evidence comparison of main effects of tillage system (CT, conventional tillage and NT, no-till) and placement (BC, broadcast and BD, band) and the interaction on soybean yield in soils with low (<20 mg kg^{-1}) soil test phosphorus (STP). Different letters show significance ($p<0.10$) and NS, non-significant means. Numbers listed in parenthesis are the total soybean yield mean observations used in the analysis.

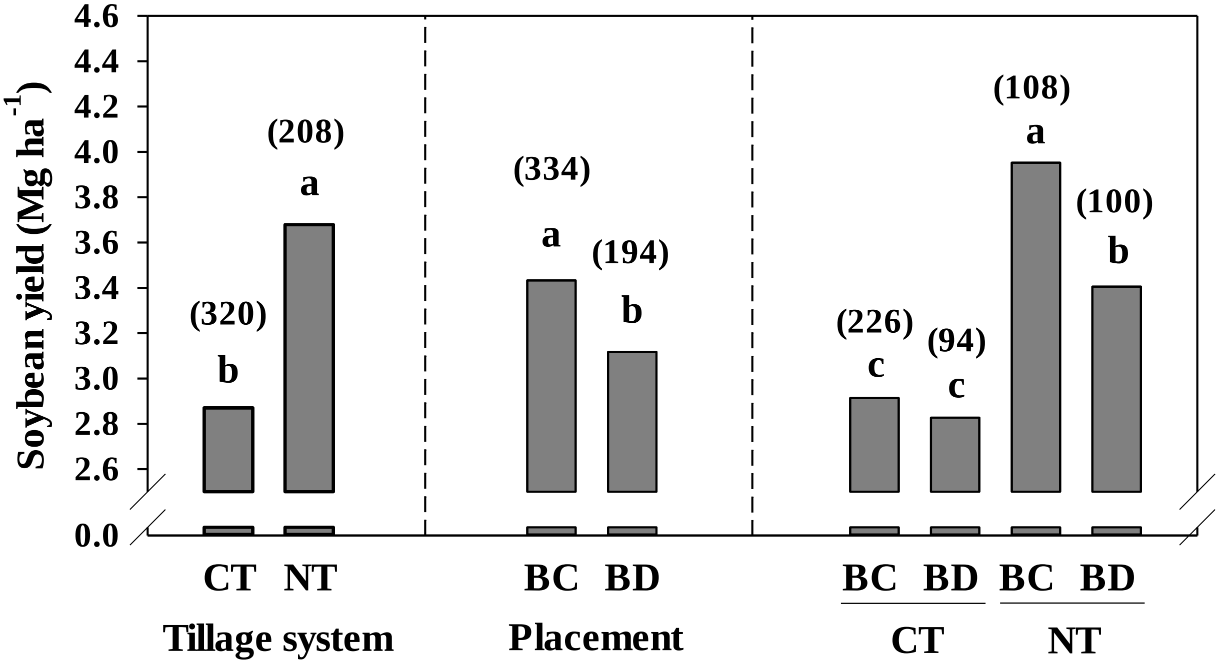

Figure 2. 6. All evidence comparison of main effects of tillage system (CT, conventional tillage and NT, no-till) and placement (BC, broadcast and BD, band) and the interaction on soybean yield in soils with high (>20 mg kg^{-1}) soil test phosphorus (STP). Different letters show significance (*p<0.10)*. Numbers listed in parenthesis are the total soybean yield mean observations used in the analysis.

Chapter 3 - Corn response to long-term phosphorus application rate and placement under strip-tillage

ABSTRACT

The agronomic and environmental effect of phosphorus (P) fertilizer placement and application rate are often noticeable after multiple years of application. The objective of this study was to evaluate the long-term effects of P placement on corn (*Zea mays* L.) under strip-tillage. The study was conducted at two locations in Kansas; Republic Co. under supplemental irrigation and Franklin Co. dry land, with a corn-soybean (*Glycine max* L.) crop rotation from 2006 to 2015. Strip-tillage was conducted before corn and soybeans were planted without previous tillage. Treatments included a control, starter only at 10 kg P ha^{-1}, and two P rates of 20 and 39 kg P ha^{-1} with placements broadcast, broadcast with starter combination, deep band, and deep band with starter combination, applied before planting corn. Additional treatments included broadcast 20 kg P ha^{-1} to soybean following applications of broadcast with starter at 20 and 39 kg P ha^{-1} to corn, totaling 39 and 59 kg P ha^{-1} for the two-year rotation. Results show the increasing treatment significance on V-6 whole plant P uptake, ear leaf and grain P concentration, and yield over the course of this study. Significant of treatment effects across years could be explained by changes in STP levels for different placements. Starter placement increased early P uptake when combined with broadcast and deep band applications. In Republic Co., starter increased yields by 0.41 and 0.38 Mg ha^{-1} at the 20 and 39 kg P ha^{-1} rates compared to broadcast applications. Early P uptake at V-6 was consistently higher with deep band applications with starter, but this did not translate into yield. The long-term evaluation of P placement in this study showed that deep-band P placement seldom resulted in higher yields, however there could be some environment advantage with deep band applicaitons. The use of starter fertilizer increased average grain yield, particularly for high-yielding systems.

Keywords: Phosphorus, strip-tillage, corn, fertilizer placement, starter, deep band, broadcast

INTRODUCTION

Strip-tillage allows for residue to be incorporated into a narrow band and prepares the soil for planting. The addition of deep band application of fertilizer with the strip-tillage allows for concentrated fertilizer placement directly below the planted seed. However, in reduced tillage systems, P stratification can potentially affect crop yield due to lack of nutrient acquisition (Mallarino and Borges, 2006). Nutrient stratification is attributed to the lack of incorporation of nutrients (Robbins and Voss, 1991) and excessive crop residue (Karlen et al., 1991). Therefore, in reduced tillage systems, more emphasis should be put on P fertilizer placement.

Surface P fertilizer applications increase stratification (Eckert, 1985; Mullen and Howard, 1992). However, several studies have shown that broadcast applications can increase yields compared to banding (Bordoli and Mallarino, 1998). Kovar and Barber (1987) showed that the greatest recovery of P occurred when at least five percent of the soil volume was fertilized. Starter and deep band applications of P fertilizer create an area of concentrated P fertilizer. A consistent yield response to placement is with a 5 cm to the side and 5 cm below the seed starter application (Randall and Hoeft, 1998). Several studies have compared starter application to broadcast or deep band applications (Walker et al., 1984; Rehm, 1986), but none of which compare combination applications of starter with broadcast and deep band applications. The combination of broadcasting and banding could improve crop uptake as the banding component would allow for readily available P, and broadcast could increase nutrients throughout the surface portion of the soil. The use of plant tissue testing to monitor P uptake has also shown the highest recovery of P with subsurface band applications (Schwab et al., 2006), however, this increase P recovery has not translated into increased yields compared to broadcast (Barber, 1980; Mallarino et al., 1999).

Many studies suggest that soil test P (STP) levels can have a greater effect on plant response compared to P fertilizer placement. Yield response is small or nonexistent when STP ranges between 15 and 20 mg P kg^{-1} (Mallarino et al., 1991; Mallarino and Blackmer, 1992; Webb et al., 1992). However, in low STP, corn yields are increased with the application of P (Rehm, 1986). In the Midwest, critical levels for corn production can range from 15 to 25 mg kg^{-1} (Liekam et al., 2003; Vitosh et al., 1995; Mallarino et al., 2013). Expectations for greater yields have led to higher fertilizer applications potentially increasing soil P, especially when only 15 to 30 percent of P applied is taken up by crops within the application year (Syers et al., 2008). Thus, if only 30 percent is taken up with fertilizer applications to corn, residual P would be available for the following crop. Therefore, creating a need for a long-term study looking at fertilizer placement on corn, soybean, and changes in STP in reduced tillage systems. 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

This study was established in 2006 and conducted at two locations in Kansas; Franklin county and Republic county. The soil at the Franklin Co. 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 Republic Co. 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 Republic Co. location had a history of no-till production practices for more than five years before the implementation of this study, while the Franklin Co. location was managed with conventional tillage prior to the implementation of the study. The Republic Co. location received supplemental irrigation, and Franklin Co. was rain fed. The corn-soybean crop rotation is common for both regions, 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 Franklin Co. and Republic counties respectively. Corn planting dates during the 10 years of the study were between April-15 andMay-15 at both locations. Herbicide and insecticide applications were made as needed. Both locations received strip-tillage before corn, whereas soybeans were planted with no prior tillage. Corn and soybean were both planted in the row of the previous years' crop.

The experimental design was a randomized complete block design with four replications and a total of 12 treatments. Treatments included a control with no P application and starter fertilizer at 10 kg P ha^{-1}. Eight treatments were included as total P rates of 20 and 39 kg P ha^{-1} with four placement combinations: broadcast, broadcast with starter combination, deep band, and deep band with starter combination applied before planting corn. At the 20 kg P ha^{-1} rate, treatments consisting of a combination of broadcast with starter and deep band with starter were applications with 10 kg P ha^{-1} (broadcast or deep band) and 10 kg P ha^{-1} as starter. At the 39 kg P ha^{-1} rate, treatments consisting of a combination of broadcast with starter and deep band with starter were split applications with 29 kg P ha^{-1} (broadcast or deep band) with 10 kg P ha^{-1} as starter. At the Republic County location, starter fertilizer was applied on the soil surface with the planter using ammonium polyphosphate (APP), 10-15-0 (N-P-K). At the Franklin County location, starter was applied 5 cm to the side and 5 cm below the seed with the planted using APP. Broadcast treatments were applied by hand to the soil surface before planting using triple superphosphate (TSP; 0-20-0). Deep band applications were applied with the strip-till operation at approximately 15 cm below the soil surface before planting using APP. Starter fertilizer application was applied at a rate of 10 kg P ha^{-1}, and the balance was applied as broadcast or deep band to total 20 and 39 kg P ha^{-1}.

Two additional treatments included fertilizer applied to soybeans at a rate of 20 kg P ha^{-1} broadcast in addition to fertilizer applied before corn. From 2006-2010, one treatment consisted 29 kg ha^{-1} broadcast with starter (10 kg ha^{-1}) combination with the additional soybean application for a total of 60 kg P ha^{-1} for the two-year rotation. In 2011 and for the duration of the study, this treatment was converted to 20 kg ha^{-1} total applied to corn as 10 kg ha^{-1} broadcast with starter (10 kg ha^{-1}) combination with additional soybean application for a total of 40 kg P ha^{-1}. This treatment is refered to as BC-ST-SY at 40 kg P ha^{-1} rate in tables. From 2006-2010, the final treatment consisted of 10 kg ha^{-1} deep band with starter (10 kg ha^{-1}) combination with the additional soybean application for a total 40 kg P ha^{-1} for the two-year rotation. Starting in 2011 and for the duration of the study, this treatment consisted of 29 kg P ha^{-1} total applied to corn as broadcast with starter combination with additional soybean application, for a total of 59 kg ha^{-1}. This treatment is refered to as BC-ST-SY at the 60 kg P ha^{-1} rate in tables. Broadcast applications were by hand to the soil surface at soybean planting using TSP.

The implement used in Republic Co. was a Brothers Equipment Inc. (Friend, NE) strip-till unit with straight chisel point shank knife, wavy coulter, rolling basket, and fertilizer application with an electric pump (Delavan Pumps Inc., model 5850-101E, Minneapolis, MN) using speed and pressure to control rates. The strip-till implement used in Franklin Co. 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) to balance N in all treatments, therefore preventing a nitrogen effect from different rates of APP application. In Franklin Co., N fertilizer application was balanced for all plots to a total of 134 kg ha^{-1} $year^{-1}$, applied before corn as a deep band. From 2006 to 2010 in Republic Co., a total application rate of N was 190 kg ha^{-1} $year^{-1}$ using UAN was balanced in deep band applications. From 2011 through the duration of the study, a blanket application of 224 kg N ha^{-1} using anhydrous ammonia (AA; 82-0-0) 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 12 individual cores taken at random to get a representative sample at the 15 cm sampling depth for the study area. Soil pH was determined in a 1:1 (soil:water). Soil test P (STP) levels were determined colorimetrically using the Mehlich-3 extraction (Frank et al., 1988) 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). Rainfall and air temperature were collected for each location using automated weather stations located within one kilometer from the study area.

Ten above-ground whole-plant samples were taken at the V-6 growth stage (Ransom and George, 2013) for early growth evaluation, and fifteen corn ear leaf samples were collected at the R-2 growth stage from the two center rows. The ear leaf is described as the leaf attached to the uppermost ear. Plant samples were dried in a forced air oven at 60 degree Celsius for a minimum of 4 days. After drying, plants were ground with a Wiley Mill grinder to pass a 2 mm screen. Tissue samples were digested with a sulfuric acid and hydrogen peroxide digest and P concentration was determined by inductively coupled plasma atomic emission spectroscopy

(ICP-AES) (Thomas et al., 1967). Whole plant biomass and P concentrations were used to calculate total P uptake at the V-6 growth stage. The two center rows of each plot were harvested with a plot combine. Grain weight was recorded and adjusted for 155 g kg^{-1} moisture. Grain sample was ground to pass a 2 mm screen and digested following Thomas et al. (1967) and analyzed for P concentration by ICP-AES.

Statistical analysis

Data were analyzed both by site-year and across site-years using *proc Glimmix* in SAS 9.4 (SAS, 2015) with block as a random factor and year as a repeated measure. For the analysis across sites, both site-year and block within site-year were considered as random factors. When treatment effects on corn parameters were significant by year and across years, least squared means were separated and used to interpret those significant treatment effects. Statistical significance was determined ($p<0.10$).

RESULTS AND DISCUSSION

The soil samples collected before initiating the study showed a pH of 5.8 and 6.6 for Franklin Co. and Republic Co. 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} organic matter, for Franklin Co. and Republic Co. respectively. The total precipitation and average maximum and minimum air temperatures by year from 2006 to 2015 for both locations are presented in Table 3.1. The 10-year average precipitation was greater for Franklin Co. than for Republic Co. at 996 and 762 mm per year respectively. However, the Republic Co. location did receive supplemental irrigation.

The significance of F values for the fixed effects of fertilizer treatments showed lower values for recent years compared to the initial years of the study for all the parameters evaluated in this study (Table 3.2). This trend suggests that multiple years of P fertilizer application rate and placement combined with P removal with the harvested grain can result in significant crop response only after multiple years. Producers typically use the same fertilizer management system for multiple years, and this study provides evidence of the long-term effect of certain management practices when implemented over time. All corn parameters showed treatment significance when averaged over 10-years.

Franklin County

In Franklin Co., V-6 whole plant samples were not collected in 2006 or 2010 (Table 3.3). Year to year whole plant samples taken at the V-6 growth stage generally had greater P uptake with the deep band with starter at 39 kg P ha^{-1}. Banding fertilizer has been found to increase early growth compared to broadcast (Schwab et al., 2006; Barber, 1980; Mallarino et al., 1999). Averaged over 10-years, P uptake quantities at the V-6 growth stage from broadcast with starter applications match those of deep band with the starter at both 20 and 39 kg P ha^{-1} rates (Figure 3.1). Banding fertilizer as a deep band, deep band starter, and higher application rates applied to soybeans in the rotation resulted in greater ear leaf concentrations (Table 3.3). At the 39 kg P ha^{-1} rate, ear leaf concentrations were higher with deep band and deep band with starter applications. In Franklin Co., increases in P uptake and P ear leaf concentration with starter compared to broadcast were observed for the 20 and 39 kg P ha^{-1} application rate (Figure 3.1). However, this increase did not occur in grain P or yield at either rate. Compared to deep band, there was no advantage to starter applications with deep band despite the increase in ear leaf P (Figure 3.1).

Franklin Co. yields in 2011, 2012, and 2013 were found not to have significant treatment differences. Highest corn yields were observed at the 39 kg P ha^{-1} rate with P broadcast, broadcast with starter, and deep band (Table 3.5). Belcher and Ragland 1972 showed that surface P fertilizer applications to be as efficient for corn as a combination of broadcast and banded P. In Franklin Co., the additional 20 kg P ha^{-1} broadcast to soybean did not result in an increase in yield, even though the total P applied for the two-year crop rotation was the highest of all treatments. Based on published removal coefficient values for P, a 10-year yield average for Franklin Co. of 8 Mg ha^{-1} for corn and 2 Mg ha^{-1} for soybean would result in average removal rates of 21 and 24 kg P ha^{-1} for the two-year rotation (Leikam et al., 2003). Therefore, at the highest P fertilizer application rates, no response to additional P fertilizer would be expected as removal rates are less than applied rates. However, grain P concentrations were consistently greater with higher P rates (Table 3.5).

Republic County

In Republic Co., whole plant samples were not collected in 2006, 2009, or 2010. At this location, greater biomass was observed with a combination of deep band with the starter. However, greater concentrations of P were observed with broadcast and broadcast with the starter (data not shown). The most consistent effect of placement on early P uptake was with starter applications. Greater concentrations were observed with broadcast and broadcast with starter application (Table 3.5). Additional broadcast application to soybean also resulted in greater ear leaf P. Corn ear leaf P concentration has been found to correlate with yield (Stammer and Mallarino, 2015). In Republic Co., the highest yields were observed with broadcast with starter and higher fertilizer rates (Table 3.6).

With supplemental irrigation, yields in Republic Co. were consistently higher over time and from year to year than Franklin Co. (Table 3.6). In 2012 and 2013 yields were lower than 10-year averages because a regional drought affected irrigation rates. After 2006, treatment differences were increasing significantly throughout the study (Table 3.6). Treatment differences at the Republic Co. location were greater and are likely due to high average removal rates with the corn grain yield (33 kg P ha^{-1} $year^{-1}$). The additional P applied to soybean in the two-year rotation increase early P uptake in corn, but showed no effect on corn yield.

At the 20 kg P ha^{-1} rate in Republic Co., there was a starter response compared to broadcast applications, which did result in increased yield (Figure 3.2). Previous studies showed that deep band applications increased early P uptake compared to broadcast (Schwab et al. 2006). However, there was no increase in yield as observed in other studies (Barber, 1980; Mallarino et al., 1999). At the Republic Co. location, corn responded to starter compared to deep band in early P uptake, ear leaf P, and yield at the 39 kg P ha^{-1} rate (Figure 3.2). This result shows the starter aided in increased P availability for early growth, even though deep band was applied only 15 cm below the seed.

Soil test phosphorus

Increasing significance of placement and rate on corn over the study could be attributed to changes in soil test and differences in removal rates by treatment. Soil samples taken in the spring of 2016 show changes in STP from initial samples by treatment. In Republic Co., regardless of placement and removal rates in yield, all application methods increased STP levels within the top 15 cm. Soil samples were collected in 2015 to look at the distribution of P in the top 15 cm soil at 7.6 cm increments from the row. Only treatments at the 39 kg P ha^{-1} rate with placements of broadcast, broadcast starter combination, deep band, and deep band starter combination were sampled. Soil test P levels in the top 15cm soil were 10.4, 12.6, 16.6, and 22.8 mg P kg^{-1} for broadcast, broadcast with starter, deep band, and deep band with starter. When the same rate of fertilizer is applied, concentrated nutrients in bands can result in areas of increased P concentrations. These results show the inconsistencies producers may encounter with soil sampling with different P placements, especially in long-term minimal tillage systems.

CONCLUSIONS

Results of this experiment demonstrated that long-term corn yields are affected by P placement and application rate. This study confirms the results that others have observed with increased corn yield with starter application. Also, increased early growth and P uptake from banding fertilizer were found to not necessarily translate into higher yields. Inconsistencies with early P uptake and ear leaf P concentrations have shown not to be reliable for predicting potential yield response. This study also provided detailed information on the long-term response of corn with P fertilizer placement and rates. Furthermore, results from this study suggest that corn yield level and P removal rate over time can generate a different response to P fertilizer application rate and placement after multiple years.

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Table 3. 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.

	Franklin County			Republic County		
Year	Precipitation‡	Max Temp§	Min Temp§	Precipitation	Max Temp	Min Temp
	mm	- - - - - - °C - - - - - -		mm	- - - - - - °C - - - - - -	
2006	812	20.9	7.67	680	19.8	5.13
2007	1271	19.1	7.22	975	18.2	5.32
2008	1135	17.6	5.67	1127	17.0	3.96
2009	1179	17.8	6.57	706	17.7	3.83
2010	1911	19.5	8.13	1442	18.2	6.18
2011	734	20.2	7.88	523	19.1	5.55
2012	536	22.5	8.83	415	20.9	5.61
2013	734	17.9	5.87	571	17.7	4.46
2014	687	18.2	5.96	482	17.8	4.69
2015	962	19.6	7.38	702	19.3	5.72
Average†	996	19.3	7.12	762	18.5	5.04

† 10-year 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 3. 2. Significance of F values for the fixed effects of fertilizer treatments on corn biomass, phosphorus (P) concentration, and P uptake in whole plant samples taken at the V-6 growth stage, P concentration in corn ear leaf at R-2 and grain after harvest, and corn grain yield at Franklin and Republic counties for the 10-year study and average across years.

	Year										
Parameter†	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Across years‡
	- $p > F$ -										
	Franklin County										
V-6 P uptake	---§	0.520	0.541	0.001	---	0.001	0.219	0.001	0.001	0.001	0.001
Ear Leaf P	0.516	0.036	0.048	0.002	---	0.001	0.001	0.001	0.001	0.001	0.001
Grain P	0.049	0.589	0.009	0.001	0.001	0.583	0.199	0.001	0.001	0.002	0.001
Yield	0.003	0.271	0.715	0.013	0.011	0.568	---	0.088	0.068	0.001	0.014
	Republic County										
V-6 P uptake	---	0.001	0.001	---	---	0.001	0.001	0.001	0.001	0.005	0.001
Ear Leaf P	0.575	0.223	0.003	0.003	0.015	0.001	0.001	0.006	0.001	0.001	0.001
Grain P	0.873	0.518	0.160	0.003	0.021	0.017	0.302	0.038	0.086	0.001	0.001
Yield	0.878	0.001	0.001	0.001	0.010	0.001	0.006	0.001	0.010	0.002	0.001

† V-6 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 R-2 growth stage; Grain P, P concentration in grain following harvest.

‡ Significance of sample averaged across 10-years.

§ Whole plant samples were not collected in 2006 or 2010 in Franklin county or 2006, 2009, or 2010 in Republic county. Ear leaf samples were no collected in 2010 in Franklin county. Corn was harvested in Franklin county 2012, but due to extremely low yields, they were not included.

Table 3. 3. The effects of fertilizer rate and placement on phosphorus (P) uptake in whole-plant corn samples taken at the V-6 growth stage and P concentrations in ear leaf samples taken at R-2 growth stage in Franklin county.

		10 kg P ha^{-1}†	20 kg P ha^{-1}				39 kg P ha^{-1}					59 kg P ha^{-1}
Year§	Control	ST‡	BC	BC-ST	DB	DB-ST	BC	BC-ST	DB	DB-ST	BC-ST-SY	BC-ST-SY
						V-6 whole plant P uptake, mg plant^{-1}						
2007	27.3	25.2	26.0	25.2	28.2	27.6	28.5	29.6	29.8	31.5	24.6	28.9
2008	41.6	51.5	50.5	45.9	54.6	59.2	66.2	53.7	51.9	58.9	55.6	56.0
2009	7.9f¶	14.0bc	8.6f	9.9ef	12.5cd	15.8b	11.7de	14.3bc	13.0cd	19.6a	15.5b	15.9b
2011	7.7g	11.1f	12.9def	12.6def	12.6ef	15.4abc	11.8ef	14.9bcd	11.5ef	16.6ab	13.7cde	17.6a
2012	11.3	13.6	12.1	12.0	13.2	13.9	12.6	15.7	15.8	13.1	12.3	13.8
2013	25.9f	33.5de	29.6ef	34.2de	37.0cd	40.5bc	42.8abc	47.8a	43.1abc	48.0a	42.4abc	45.4ab
2014	13.1f	18.7cde	17.2ef	18.9cde	20.5bcde	18.8cde	19.7bcde	28.7a	22.0bcd	23.7b	18.0de	22.5bc
2015	19.0f	26.9ef	31.5de	35.8cd	39.1cd	42.0bc	40.1c	48.9a	51.6a	56.7a	41.2bc	56.6a
Average	18.1f	22.9de	22.4e	25.5cde	27.8abc	27.0bcd	23.7de	28.6abc	30.4ab	32.2a	26.7cde	30.7ab
						Ear leaf P, g kg^{-1}						
2006	2.3	2.0	2.3	2.1	2.0	2.3	2.4	2.3	1.9	2.1	2.0	2.1
2007	4.0cde¶	4.3bcd	3.9de	5.1a	4.3bcd	4.6abc	3.6e	4.4bcd	4.4bcd	4.7ab	4.3bcd	4.6abc
2008	2.3d	2.6cd	2.8cd	2.8bcd	3.0bc	3.0bc	3.0bcd	3.2bc	3.5b	4.2a	3.2bc	2.9bcd
2009	2.3c	2.6bc	2.5bc	2.7b	2.6bc	2.7b	2.6bc	2.7b	3.2a	3.3a	2.8b	2.7b
2011	2.0i	2.5gh	2.4h	2.8def	2.7fg	2.8def	2.8ef	3.0cde	3.1bc	3.2ab	3.0bcd	3.4a
2012	2.3i	2.8fgh	2.7gh	3.0def	3.2cd	2.9efg	2.7h	3.2cde	3.8a	3.6ab	3.4bc	3.3bc
2013	1.7g	1.9efg	1.8fg	2.1defg	2.5bc	2.5bcd	2.0efg	2.2cdef	3.1a	2.7ab	2.3cde	2.6bc
2014	2.0f	2.6de	2.3ef	2.8cd	2.9bcd	2.8cd	2.8bcd	2.8bcd	3.1b	3.9a	2.9bc	3.1bc
2015	2.2g	2.5f	2.9e	3.3d	3.2de	3.2d	3.6bc	3.5c	3.6bc	3.8ab	3.7bc	4.1a
Average	2.4g	2.6f	2.6f	2.9cde	2.9de	3.0cde	2.8ef	3.0cd	3.3b	3.5a	3.0cde	3.2bc

† Rate of total P fertilizer (kg P ha^{-1}) applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer ST, 5 cm by 5 cm fertilizer starter band of 10 kg P ha^{-1}; BC, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast application of 20 kg ha^{-1}.

§ V-6 whole plant samples were not collected in 2006 and 2010 and ear leaf samples in 2010; average over years by location.

¶ Different letters in rows by year and across years indicate significant differences (*$p<0.10$*).

Table 3. 4. The effects of fertilizer rate and placement on phosphorus (P) concentration in corn grain following harvest and corn grain yield in Franklin county.

		10 kg P ha^{-1}†	20 kg P ha^{-1}				39 kg P ha^{-1}					59 kg P ha^{-1}
Year§	Control	ST‡	BC	BC-ST	DB	DB-ST	BC	BC-ST	DB	DB-ST	BC-ST-SY	BC-ST-SY
- - - Grain P, g kg^{-1} - - -												
2006	2.2e¶	2.4cde	2.5bcd	2.3de	2.6abc	2.7ab	2.6abc	2.7ab	2.8a	2.7ab	2.5abcd	2.6abcd
2007	2.3	2.5	2.6	2.7	2.3	2.3	2.8	2.7	2.4	2.5	3.0	2.8
2008	2.2d	2.3d	2.7bc	2.6bc	2.5cd	2.7bc	3.0a	2.7abc	2.7bc	2.7bc	2.8ab	2.8ab
2009	2.1g	2.2fg	2.5de	2.6bcd	2.5de	2.4ef	2.6cde	3.0a	2.8ab	2.8bc	2.7bc	2.8bc
2010	2.3f	2.6e	2.9bcd	2.8cd	2.8d	2.9abcd	2.9bcd	3.0abc	3.0abc	3.0abcd	3.1a	3.0ab
2011	2.4	2.7	2.6	2.6	2.6	2.7	2.8	2.7	2.9	2.8	2.7	2.9
2012	2.7	2.4	2.6	2.2	2.4	2.5	2.6	2.6	2.5	2.5	2.6	2.5
2013	2.6h	2.9g	2.8h	3.2ef	3.4def	3.5bcd	3.2f	3.4cde	3.7ab	3.9a	3.4def	3.7abc
2014	1.6f	1.9e	2.0de	2.2cd	2.0e	2.0de	2.3bc	2.3bc	2.4ab	2.5a	2.3bc	2.4ab
2015	2.1e	2.3de	2.3cd	2.4bcd	2.3cde	2.3cde	2.8a	2.6ab	2.5abc	2.6ab	2.6ab	2.7a
Average	2.2d	2.4c	2.5b	2.6b	2.6b	2.6b	2.8a	2.8a	28a	2.8a	2.8a	2.9a
- - - Yield, Mg kg^{-1} - - -												
2006	5.1f	5.3ef	6.0abcd	5.8bcde	6.1abc	6.4ab	6.3ab	6.3ab	6.4a	5.6def	5.7cde	6.5a
2007	5.9	6.4	6.0	6.5	6.5	6.6	6.2	6.5	6.5	6.3	6.4	6.4
2008	8.1	8.9	8.9	9.6	9.4	8.8	9.0	9.0	8.4	8.7	8.7	9.3
2009	8.7de	8.8de	8.9bcde	8.9cde	9.6a	8.9bcde	9.4abc	9.3abcd	8.9cde	8.7e	9.5ab	8.7e
2010	5.5b	5.6b	6.2a	6.4a	6.4a	6.7a	6.3a	6.3a	6.4a	6.2a	6.4a	6.5a
2011	4.5	4.8	4.9	5.0	4.7	5.3	5.3	5.5	5.4	5.2	5.0	5.2
2013	6.5b	7.9a	7.4a	8.1a	7.8a	8.0a	7.6a	7.7a	7.7a	7.7a	7.6a	7.9a
2014	7.2abc	6.2bcd	7.4ab	6.2bcd	5.8cd	7.1abc	7.8a	7.3ab	7.6ab	5.1d	5.3d	6.6abcd
2015	8.2e	9.0d	9.4bcd	9.6abc	9.5abc	9.2cd	9.9a	9.9a	9.8ab	9.8a	9.6abc	9.8a
Average	6.7e	7.1d	7.5abc	7.5abc	7.5abc	7.7ab	7.8a	7.7ab	7.6ab	7.2cd	7.4bcd	7.6ab

† Rate of total P fertilizer (kg P ha^{-1}) applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer ST, 5 cm by 5 cm fertilizer starter band of 10 kg P ha^{-1}; BC, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast application of 20 kg ha^{-1}.

§ Corn yield was collected in 2012, but due to extremely low yields, they were excluded from analysis; average over years by grain and yield.

¶Different letters in rows by year and across years indicate significant differences (*$p<0.10$*).

Table 3. 5. The effects of fertilizer rate and placement on phosphorus (P) uptake in whole-plant corn samples taken at the V-6 growth stage and P concentrations in ear leaf samples taken at R-2 growth stage in Republic county.

		10 kg P ha^{-1}†	20 kg P ha^{-1}				39 kg P ha^{-1}					59 kg P ha^{-1}
Year§	Control	ST‡	BC	BC-ST	DB	DB-ST	BC	BC-ST	DB	DB-ST	BC-ST-SY	BC-ST-SY
						V-6 whole plant P uptake, mg plant^{-1}						
2007	12.3d	26.5b	20.3c	26.6b	26.1b	27.8b	23.0bc	24.6bc	27.9b	33.6a	26.2b	24.7bc
2008	40.8f	48.7de	47.3def	72.0a	46.5def	53.0cd	61.1b	43.2ef	56.4bc	68.1a	59.8b	72.0a
2011	9.5g	14.0ef	13.7f	17.1de	16.7def	17.7d	18.9cd	25.4a	21.5bc	23.8ab	18.6cd	26.6a
2012	38.9f	52.9de	51.3ef	73.4bc	61.1cde	67.2bcd	62.3bcde	76.7b	5207bcde	90.9a	70.6bc	74.9bc
2013	31.1f	48.6e	43.3e	51.2de	52.8de	52.8de	56.9cd	73.2a	63.3bc	76.5a	62.6bc	66.1b
2014	32.7g	51.3ef	47.0f	64.2bcd	50.6ef	65.2bc	55.0def	61.1cd	65.0cd	70.3ab	58.2cde	76.9a
2015	24.5d	48.5bc	36.2cd	51.7ab	44.0bc	53.4ab	53.9ab	53.4ab	49.1ab	53.0ab	61.1a	54.2ab
Average	26.9g	41.3e	37.3f	43.6de	45.9cde	50.2c	51.3bc	49.0cd	50.6c	59.7a	51.3bc	56.8ab
						Ear leaf P, g kg^{-1}						
2006	2.0	2.2	2.3	2.2	2.2	2.2	2.3	2.3	2.3	2.2	2.2	2.3
2007	2.2	2.7	2.8	2.7	2.6	2.7	2.7	3.0	2.6	3.0	2.6	2.6
2008	2.2d	2.5bc	2.5bc	2.6ab	2.7ab	2.7ab	2.8a	2.8a	2.3cd	2.6ab	2.7ab	2.7a
2009	2.1f	2.5bcde	2.3ef	2.3cdef	2.3ef	2.5bcd	2.4cde	2.6ab	2.3def	2.6bc	2.8a	2.4cde
2010	2.3e	2.5de	2.6cd	2.5cd	2.6cd	2.6cd	2.9a	2.7abcd	2.5cd	2.7bcd	2.8ab	2.8abc
2011	2.1f	2.3e	2.5cde	2.5bcd	2.5cde	2.5cde	2.7bc	2.7ab	2.5cde	2.4de	2.9a	2.6bcd
2012	1.9d	2.0cd	2.2bc	2.1bc	2.0cd	2.0cd	2.4a	2.4ab	2.1cd	2.2bc	2.3ab	2.5a
2013	2.1d	2.2bc	2.1cd	2.3bc	2.1cd	2.4ab	2.3bc	2.3bc	2.1cd	2.4ab	2.5a	2.4ab
2014	1.6d	1.8cd	2.1bc	2.1bc	1.7d	1.8cd	2.2ab	2.3ab	1.8d	2.1bc	2.2ab	2.4a
2015	1.8f	2.2de	2.3cd	2.4bc	2.0ef	2.3cd	2.5ab	2.6ab	2.2d	2.4bc	2.7a	2.5ab
Average	2.0g	2.3def	2.4cde	2.4c	2.3f	2.4cd	2.5ab	2.6a	2.3ef	2.5bc	2.6a	2.5ab

† Rate of total P fertilizer (kg P ha^{-1}) applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer ST, 5 cm by 5 cm fertilizer starter band of 10 kg P ha^{-1}; BC, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast application of 20 kg ha^{-1}.

§ V-6 whole plant samples were not collected in 2006, 2009, and 2010; average over years by location.

¶ Different letters in rows by year and across years indicate significant differences (*$p<0.10$*).

Table 3. 6. The effects of fertilizer rate and placement on phosphorus (P) concentration in corn grain following harvest and corn grain yield in Republic county.

		10 kg P ha^{-1}†	20 kg P ha^{-1}				39 kg P ha^{-1}					59 kg P ha^{-1}
Year§	Control	ST‡	BC	BC-ST	DB	DB-ST	BC	BC-ST	DB	DB-ST	BC-ST-SY	BC-ST-SY
						Grain P, g kg^{-1}						
2006	2.3	2.4	2.3	2.3	2.2	2.2	2.3	2.5	2.4	2.5	2.4	2.3
2007	2.6	2.6	2.3	2.5	2.2	2.4	2.6	2.5	2.6	2.3	2.6	2.5
2008	2.4	2.6	2.6	2.6	2.7	2.8	3.0	2.7	2.8	2.9	2.9	2.9
2009	1.8d¶	2.2bc	2.2c	2.4abc	2.4abc	2.5a	2.2c	2.4abc	2.2c	2.5a	2.6a	2.5a
2010	2.2d	2.2d	2.4bcd	2.3cd	2.4bcd	2.5abc	2.7a	2.7a	2.4bcd	2.6ab	2.6ab	2.5abcd
2011	2.1c	2.2bc	2.1c	2.5a	2.2bc	2.5ab	2.5a	2.5a	2.5ab	2.5ab	2.6a	2.4ab
2012	2.1c	2.1c	2.5ab	2.1c	2.2bc	2.2bc	2.6a	2.4abc	2.3bc	2.3abc	2.3abc	2.1abc
2013	1.8c	1.9bc	1.8c	2.1ab	2.4a	2.3a	2.1ab	2.3a	2.3a	2.2a	2.2a	2.3a
2014	2.3e	2.6cde	2.6bcd	2.5de	2.7abcd	2.7abcd	2.6ab	2.7abcd	2.7abcd	2.9abc	2.7abcd	3.0a
2015	1.8e	2.0de	2.2cd	2.3c	2.3bc	2.4bc	2.4bc	2.6ab	2.3c	2.4bc	2.7a	2.8a
Average	2.1e	2.3d	2.3d	2.4cd	2.4cd	2.4bc	2.5ab	2.5ab	2.4bc	2.5ab	2.5a	2.5ab
						Yield, Mg kg^{-1}						
2006	11.2	11.7	11.8	12.0	12.1	11.8	12.1	11.9	11.8	11.9	11.1	12.0
2007	11.4c	13.9b	14.0ab	14.5ab	14.5ab	14.3ab	14.4ab	14.5ab	14.4ab	14.4ab	14.4ab	14.6a
2008	12.0e	14.3abc	13.8cd	14.8a	14.0bcd	14.6ab	13.6d	14.4ab	14.3abc	14.8a	14.4ab	14.3ab
2009	14.0c	16.2ab	16.1ab	17.0a	15.9b	17.0a	16.5ab	16.8a	16.0ab	16.6ab	17.0a	16.7ab
2010	11.8b	13.7a	13.8a	13.7a	14.1a	14.2a	14.0a	14.5a	13.5a	13.7a	14.5a	14.1a
2011	11.2d	13.0c	13.5bc	13.9abc	13.2c	13.8abc	13.7abc	14.3ab	13.8abc	13.8abc	14.6a	13.1c
2012	6.60c	7.80b	7.80b	7.80ab	8.10ab	7.90ab	8.30ab	8.00ab	8.00ab	8.30ab	7.80b	8.80a
2013	6.90g	8.10cde	7.30fg	8.40bcde	7.90ef	9.00ab	8.00def	8.80abc	7.90ef	8.50bcde	9.30a	8.70abcd
2014	10.0e	12.5a	10.8de	12.1abc	11.1cde	11.8abcd	11.6abcd	12.4ab	11.3bcd	12.2ab	11.8abcd	12.7a
2015	11.3c	13.9b	14.0ab	14.7ab	12.3c	14.5ab	14.4ab	14.8ab	13.8b	14.8ab	15.3a	13.7b
Average	10.5e	12.4cd	12.2d	12.8ab	12.3d	12.8ab	12.7abc	13.1a	12.5bcd	13.0a	13.1a	13.0a

† Rate of total P fertilizer (kg P ha^{-1}) applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer ST, 5 cm by 5 cm fertilizer starter band of 10 kg P ha^{-1}; BC, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast application of 20 kg ha^{-1}.

§ 2012 and 2013 corn yields were lower due to regional drought; Average over years by grain and yield.

¶ Different letters in rows by year and across year indicate significant differences (*$p<0.10$*).

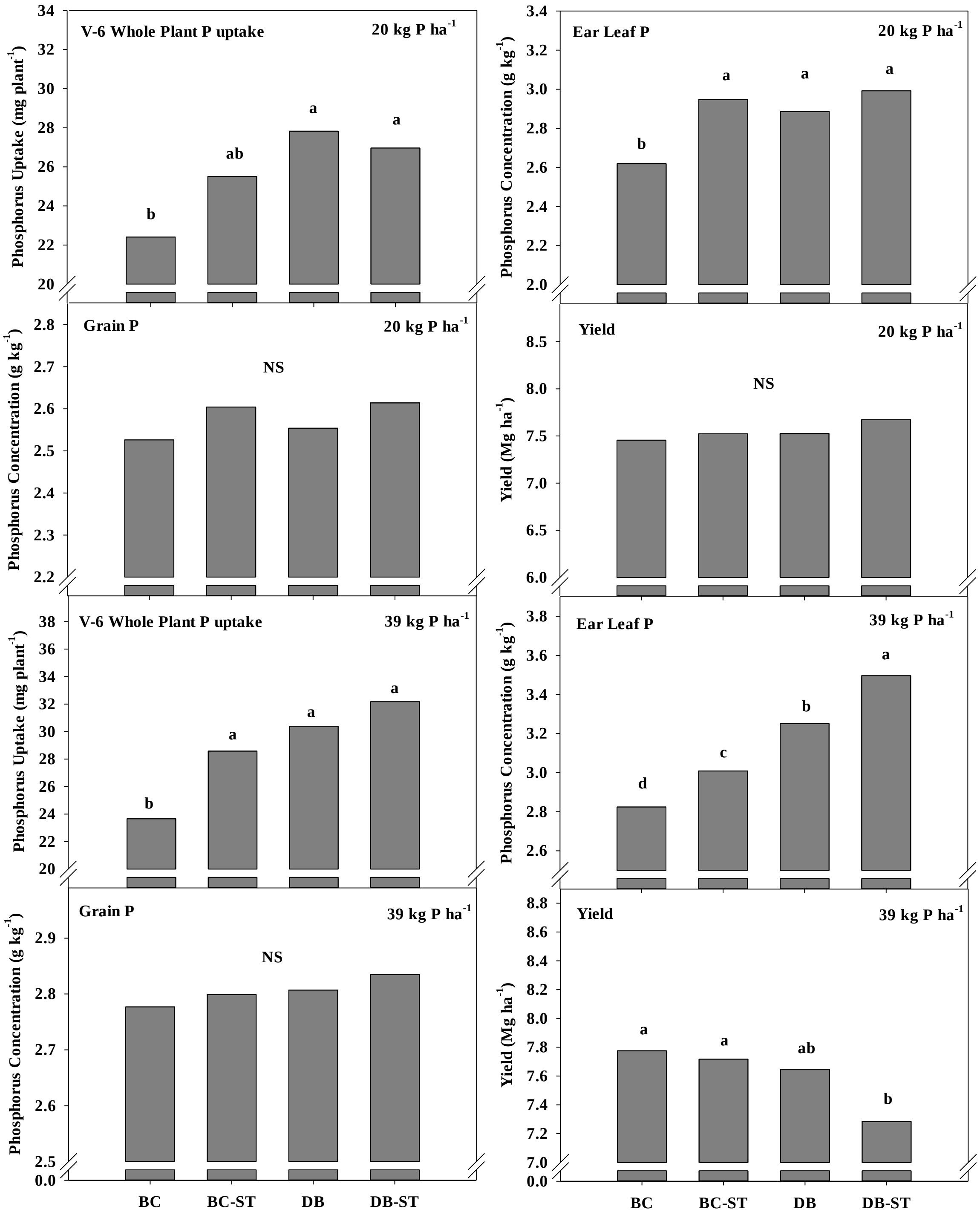

Figure 3. 1. Average early P uptake in whole plant samples taken at the V-6 growth stage, P concentration in ear leaf samples collected at R-2, grain samples collected at harvest, and corn grain yield in Franklin County. Averages are comparing placement broadcast (BC), deep band (DB), broadcast with starter combination (BC-ST), and deep band with starter combination (DB-ST) effects at 20 and 39 kg P ha^{-1} rate. Different letters indicate significance and NS, non-significance (*p<0.10)*.

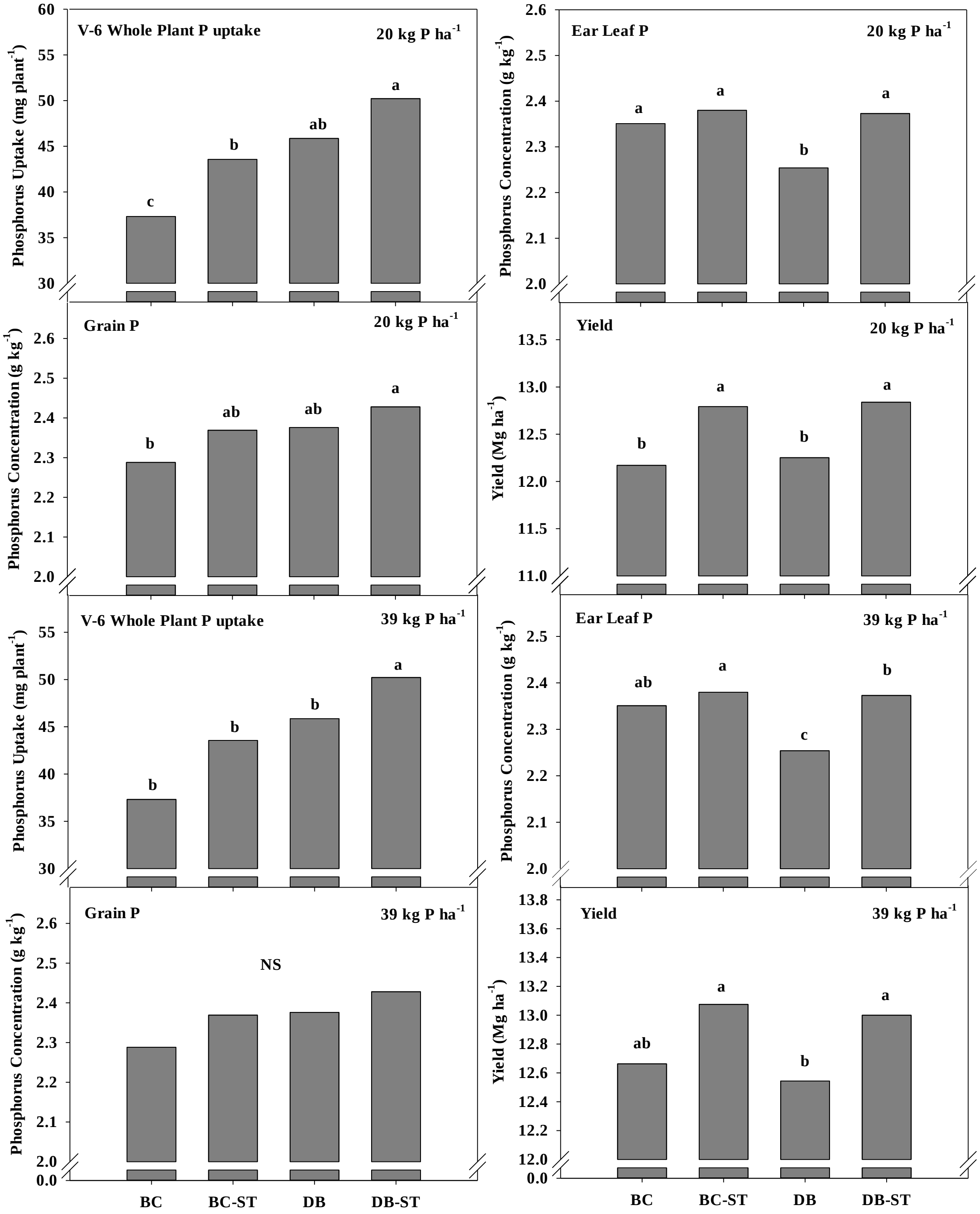

Figure 3. 2. Average early P uptake in whole plant samples taken at the V-6 growth stage, P concentration in ear leaf samples collected at R-2, grain samples collected at harvest, and corn grain yield in Republic County. Averages are comparing placement broadcast (BC), deep band (DB), broadcast with starter combination (BC-ST), and deep band with starter combination (DB-ST) effects at the 20 and 39 kg P ha^{-1} rate. Different letters indicate significance and NS, non-significance (*p<0.10)*.

Chapter 4 - Economic evaluation of long-term phosphorus placement in a corn-soybean rotation under strip-tillage

ABSTRACT

The economic implications of the right placement and rate of phosphorus (P) fertilizer for a corn (*Zea mays* L.) -soybean (*Glycine max* L.) rotation can be better evaluated with a long-term management history. The objectives of this study were to determine the relative profitability of P fertilizer placement and rate in corn and soybean rotations under strip-tillage. Agronomic studies established in 2006 and evaluated for ten years at two locations were used to assess the economic effects of P placement and rate. Treatments included a control with no P, starter only (ST) at 10 kg P ha^{-1}, and two P rates of 20 and 39 kg P ha^{-1} applied as broadcast, broadcast-starter combination, deep band, and deep band-starter combination, applied before planting corn. Two additional treatments were applied as broadcast 20 kg P ha^{-1} to the subsequent soybean crop to corn as broadcast-starter combination at 20 and 39 kg P ha^{-1}, totaling 39 and 59 kg P ha^{-1} for the two-year rotation. Fixed and varying prices and costs were used to calculate partial budgets to determine the relative profitability of these management systems compared to the control treatment. Results showed little differences between using fixed versus varying prices and costs. In Franklin Co., deep band applications resulted in an 8 percent higher net return compared to broadcast at 39 kg P ha^{-1} rate. In Franklin Co., there was no consistent net return to starter application. Soybean applications of 20 kg P ha^{-1} resulted in no increase in net return. However, at the Republic Co. location, highest net returns were observed with 20 kg P ha^{-1} applied as broadcast with starter combination with an additional 20 kg P ha^{-1} broadcast to soybean. At this high yielding location, net returns from starter application were observed. The use P fertilizer as starter application can result in a more consistent return for high yielding fields, such as in Republic Co. Based on our study, if using strip-tillage, fertilizer application should be completed during this tillage pass to maximize net return.

Keywords: phosphorus, strip-tillage, placement, starter, deep band, broadcast, net return, corn, soybean.

INTRODUCTION

Few published studies consider both the productivity as well as profitability of fertilizer placement and rate, and even fewer of the long-term effects of specific fertilizer management systems. With increasing production costs and declining crop prices, profit margins can be affected significantly, thus emphasizing the need for optimum management of crop inputs. In the Midwest, increasing adoption of strip-tillage as a reduced tillage system has led to increased use of deep band fertilizer placement as fertilizer can be applied in the same pass. Deep band fertilizer placement directly below the plant at the same time as strip-tillage typically results in no additional cost for fertilizer application. Previous studies have shown the most consistent yield response to low rates of P fertilizer applied with the planter (starter) (Randall and Hoeft, 1998). Compared to deep banding, broadcast applications have resulted in higher corn yields (Barber, 1980; Mallarino et al., 1999). In systems using strip-tillage, a separate broadcast application would require additional application costs, raising the question if additional production costs would limit net profit.

To decrease input costs, many producers apply non-mobile nutrients at one time for multiple years. A good example of this is applying P recommended rates for both crops in a corn-soybean rotation to the most responsive corn crop (deMooy et al., 1973). Residual effects of fertilization have been observed for 7 to 9 years after application, therefore long-term studies need to be evaluated (Kamprath, 1967). However, soybean show significant yield response to fertilizer P application (Buah et al., 2000).

Agronomic studies with an economic analysis of tillage have been limited to comparisons in corn-soybean rotations (Williams et al., 1990), deep tillage in soybean production (Popp et al., 2001), tillage in various cropping systems (Parsch et al., 2001), and tillage and crop rotation (Al-Kaisi et al., 2016). However, limited studies evaluated the economic return to phosphorus fertilizer placement for a corn-soybean rotation under a long-term management. One study evaluated the economic responses to N and P fertilizer placement in a dual-use and grain-only wheat (*Triticum aestivum*) production system (Siji et al., 2007). This study found no differences between N surface, N and P surface, and N and P deep band applications. Net returns per treatment were not included, and the study was only conducted for three years.

Phosphorus fertilizer placement and application rate have been studied extensively over the years. However, there is a lack of economic analysis for corn and soybean production, especially evaluated under a long-term management system. The objective of this study was to determine the relative profitability of P fertilizer placement and application rate for corn and soybean rotations under strip-tillage.

MATERIALS AND METHODS

Agronomic background

The study background and crop yields of this study were outlined in Chapter 3. Briefly, the treatments were established in the spring of 2006 at two locations in Kansas; Republic County and Franklin County. The corn-soybean rotation is common in both regions, and both faces of the rotation were present every year. Therefore, the economic analysis was evaluated separately for two adjacent fields at each location, one field started with corn and the other with soybean in 2006. Each field was evaluated separately starting with corn in 2006 at the Republic Co. Field 1 and Franklin Co. Field 2; and corn in 2007 for Republic Co. Field 2 and Franklin Co. Field 1. Initial soil samples were collected in the fall of 2005; soil test P (STP) results for both locations were categorized as "very-low" at 7.6 ppm (Liekam et al., 2003).

The experimental design and treatments were described in Chapter 3. A total of twelve treatments were included; a control with no P, starter only (ST) at 10 kg P ha^{-1}, and total P rates of 20 and 39 kg P ha^{-1} with placements broadcast, broadcast with starter combination, deep band, and deep band with starter combination. At the 20 kg P ha^{-1} rate, the treatments with combination broadcast with starter and deep band with starter consisted of applications of starter at 10 kg P ha^{-1} and either broadcast or deep band at 10 kg P ha^{-1}. At the 39 kg P ha^{-1} rate, combination treatments of broadcast with starter and deep band with starter band (10 kg P ha^{-1}) at planting and either broadcast or deep band application at 29 kg P ha^{-1}. Therefore, total application rates for combination treatments were the same as broadcast and deep band at both the 20 and 39 kg P ha^{-1} rates.

Two additional treatments included fertilizer applied to soybeans at a rate of 20 kg P ha^{-1} broadcast in addition to fertilizer applied before corn. One treatment consisted 29 kg ha^{-1} broadcast with starter (10 kg ha^{-1}) combination with the additional soybean application for a total of 60 kg P ha^{-1} for the two-year rotation starting in 2006 to 2010. In 2011 and for the duration of the study, this treatment was converted to 20 kg ha^{-1} total applied to corn as 10 kg ha^{-1} broadcast with starter (10 kg ha^{-1}) combination with additional soybean application for a total of 40 kg P ha^{-1}. This treatment is refered to as BC-ST-SY at 40 kg P ha^{-1} rate in tables. The final treatment consisted of 10 kg ha^{-1} deep band with starter (10 kg ha^{-1}) combination with the additional soybean application for a total 40 kg P ha^{-1} for the two-year rotation for 2006 to 2010. Starting in 2011 and for the duration of the study, this treatment consisted of 29 kg P ha^{-1} total applied to corn as broadcast with starter combination with additional soybean application, for a total of 59 kg ha^{-1}. This treatment is refered to as BC-ST-SY at the 60 kg P ha^{-1} rate in tables. Broadcast applications were by hand to the soil surface at soybean planting using TSP.

At the Franklin Co. location, starter fertilizer was applied 5 cm to the side and 5 cm below the seed with the planter (5x5). At the Republic Co. location, starter application was applied 5 cm to the side of the seed, dribbled on the soil surface at planting. However, in the analysis, costs of using 5x5 were used assuming no yield differences between dribble surface band and 5x5 banding (Walker et al., 1984). Starter and deep band applications were made using ammonium polyphosphate (APP), 10-15-0 (N-P-K) as the source of P. Broadcast P was applied by hand to the soil surface at planting using triple superphosphate (TSP; 0-20-0). Broadcast applications were by hand to soil surface at soybean planting using TSP. Deep band was applied with the strip-till operation approximately 15 cm deep before planting using APP. All plots in the study were strip-tilled to prevent tillage effects, even if P fertilizer was not applied. At the Franklin Co. location, N rates from APP applications were balanced for all treatments in the deep band using urea-ammonium nitrate (UAN) (28-0-0). A total of 134 kg N ha^{-1} was applied to corn as deep band. At the Republic Co. from 2006 to 2010 N rates from APP applications were balanced for all treatments in the deep band using UAN at a total rate of 190 kg N ha^{-1}. Starting in 2011 and for the duration of the study, a blanket application of 224 kg N ha^{-1} was applied using anhydrous ammonia (AA) (82-0-0). Nitrogen applied via APP as a deep band was balanced using UAN at 27 kg N ha^{-1}as a deep band in every plot. A total of 251 kg N ha^{-1} was applied per plot.

The two locations differed in application methods of N and comparisons of the two systems cannot be made, but comparisons with P placement and rates were compared within location. Therefore, at the Franklin location, only N applied as UAN to balance N applied as APP in the deep band (134 kg N ha-1) fertilizer costs were included in the analysis of net returns. However, at the Republic Co. location, only the N fertilizer rates applied in the deep band to balance N (27 kg N ha^{-1}) from APP were included in calculating net returns. Anhydrous ammonia costs were not included in any analysis since the field received a blanket application, but additional costs associated with the application of N as AA were addressed below.

Economic Analysis

A partial budget approach was adopted for economic analysis two ways: i) fixed prices and costs and ii) varying prices and cost for each treatment. For the fixed analysis, 10-year average grain prices, fertilizer cost, and application costs were used to determine the net return for each treatment. Varying net return used individual year-specific prices and costs for the duration of the study. Partial net return in both cases was calculated by subtracting the fertilizer and application cost from the yield gross return for each treatment replication then calculated as a percent of the control treatment for that replication. The control treatment received no phosphorus fertilizer application for the duration of the study, however, strip-tillage was applied for all treatments.

Table 4.1 contains the average yearly grain prices received for corn and soybean in the state of Kansas were used to calculate total income for each treatment each year (NASS, 2013). Total costs were calculated as a function of fertilizer rate by fertilizer cost plus the cost of application for each treatment. Fertilizer costs used for APP, TSP, and UAN were the national averages (NASS, 2013). Starter fertilizer application costs were determined as the difference between “planting with fertilizer and insecticide attachment” and “planting without fertilizer and insecticide attachment” adapted from the Iowa Farm Custom Rate Survey (Edwards and Johanns, 2016). Broadcast costs were estimated based on dry bulk fertilizer application. The same application costs were used for both corn and soybean broadcast applications of TSP. Deep band application costs were liquid strip-till, knifed (Edwards and Johanns, 2016).

Statistical Analysis

Data analysis was completed separately for treatment effects on partial net returns using fixed prices and costs and varying prices and costs. Data were analyzed by two-year rotation, across rotations at each field within location, and across location using *proc Glimmix* in SAS 9.4 (SAS, 2015). Rotations at Republic County Field 2 and Franklin County Field 1 were 2006-2007, 2008-2009, 2010-2011, 2012-2013, and 2014-2015. Rotations at Republic County Field 1 and Franklin County Field 2 were 2007-2008, 2009-2010, 2011-2012, 2013-2014, and 2015-2016. For the analysis by two-year rotation and across field, block was used as a random factor and rotation as a repeated measure. For the analysis across sites, both two-year rotation and block within rotation were considered as random factors. When treatment effects on corn parameters were significant by rotation, across rotation at each field within location, and across locations, least square means were calculated and used to interpret significant treatment effects. Statistical significance was determined ($p<0.10$).

RESULTS AND DISCUSSION

Grain prices for corn and soybean varied throughout the 10 years of the study (Table 4.1). Fertilizer costs increased throughout the span of this study, with APP, TSP, and UAN all doubling from 2006 to 2015 (Table 4.1). The 10-year average of dry TSP fertilizer costs per kg are lower than liquid APP. However, 6 out of 10 years, the cost of APP was lower than TSP. Besides fertilizer costs, equipment and application costs may be used in deciding economically which management practice is superior.

Application method decisions could be made strictly on what equipment is available. In this study, all plots received strip-tillage even if no P fertilizer was applied and therefore deep band application costs were included for all treatments. Therefore, higher application costs occur with additional broadcast applications at an average of $10.64 per hectare (Table 4.1). If another tillage system such as no-till is used, then different results between application costs would be expected when comparing deep band and broadcast. Since starter can be applied with the planter there are few additional costs associated with application above planting. Therefore, costs of planting with fertilizer attachments and without fertilizer attachments were used as starter application costs (Table 4.1). Walker et al. (1984) showed no yield differences between starter fertilizer applied as surface dribbled or 5 cm to the side by 5 cm below the seed. Therefore, producers could save on average $3.01 per hectare if the starter fertilizer placement is surface dribbled and attain similar yield response (Table 4.1). Table 4.2 shows the yearly total precipitation and average air maximum and minimum temperatures for both Republic and Franklin counties.

Republic County

Rotation one at the Republic Co. location in Field 1 started with corn in 2006 and field 2 began with corn in 2007 (Table 4.3). Treatment differences of partial net return were only significant across rotations for Field 2 using both fixed and varying prices and costs. Individual rotations had significant treatment effects on net returns. Rotation two at Field 1 showed significant treatment effects using both fixed and varying prices and costs. In Field 2, only rotation five resulted in significant net returns using fixed prices and costs. However, the analysis using varying price and costs resulted in significant effects of treatment on partial net return (Table 4.3). Analysis for the Republic Co. location across fields and years showed no treatment differences.

The Republic Co. location included supplemental irrigation and was a highly productive location. Overall, corn yields were highest with broadcast split starter application and lowest with the deep band and lower application rates (Table 4.4). Soybean yields were significantly less with deep band applications and responded better to being fertilized.

The Republic Co. Field 1 rotation 2 showed significantly lower net returns with deep band applications using fixed and varying prices and costs (Table 4.5). There were no differences in net return when comparing additional fertilizer applied to soybean or when comparing split applications to soybean at the same fertilizer rate before corn in Field 1. The combination application of deep band with starter resulted in significantly higher net return at double the amount of fertilizer applied. In the adjacent field, Field 2, there was no treatment difference on net return using fixed prices and costs. Since prices and costs were fixed over time, the changing variable was yield. Application rates were lower than removal rates. Therefore, over the duration of the study, there was increased separation of soil test P means at this highly productive location (Chapter 4). At the Republic Co. Field 2, the highest application rate of 59 kg P ha^{-1} with 20 kg P ha^{-1} applied to soybean did not result in higher net returns compared to the same placement at a lower rate (Table 4.5). However, there were increases in soybean yield by 0.4 Mg ha^{-1} (Table 4.4).

Using varying price and costs, rotation four resulted in significant treatment effects (Table 4.5). Highest net returns were observed with deep band with starter combination P fertilizer applications, especially when analyzed across fields. Lower total costs for deep band applications and relatively greater yields with deep band applications offset the costs associated with starter applications. Higher P rates and combination of application methods to soybean at 39 kg P ha^{-1} total P rate resulted in higher net return at Field 2 at the Republic location in rotation four (Table 4.5). Research has shown that soybean respond to direct P fertilizer application (Buan et al., 2000). Lower net returns with an additional 20 kg P ha^{-1} so soybean for the two-year corn-soybean rotation indicates that yields for the two crops did not offset additional input costs.

When comparing deep band and broadcast applications, another component to consider is how N is applied. At the Republic Co. location, a blank application of N was applied using AA. For this study, additional costs of AA application were not included in the analysis. However, there are additional costs associated with AA application. The extra application cost for AA is roughly \$25.67 ha^{-1}. At that rate, an additional 0.14 Mg ha^{-1} corn yield would be required to offset application costs. Additional research is needed to evaluate the potential return for AA over deep banding N rates with strip-till application.

Franklin County

Rotation one at the Franklin Co. location began with corn in 2006 Field 2 and 2007 in Field 1 (Table 4.6). Individual rotations had significant treatment effects. However, the only general trend was treatment significance in rotations using fixed prices and costs were also significant using varying costs and prices. Using both fixed and varying price and costs resulted in significant effects of treatment on partial net returns across rotations and field.

At the Franklin Co. location, the limiting factor of crop production was water availability. Significantly lower corn yields were observed with deep band with starter combination (Table 4.7). Unlike the Republic Co. location, corn did not respond to higher P fertilizer application rates nor did soybean responded to P fertilizer application. With lower yields, both fields at the Franklin Co. location showed negative net returns depending on treatment (Table 4.8). Lower net returns with fixed prices and costs were observed at Franklin Co. Field 1 rotation two with higher application rates. The additional 20 kg P ha^{-1} applied to soybean resulted in significantly lower net returns. This result would be expected at this location due to no yield increases with additional fertilizer and other potential limiting factors. Starting with corn in 2013 for rotation four at Field 1, broadcast with starter combination resulted in lower net returns. Even though greater yields were achieved with broadcast and starter applications (Table 4.7), input costs from placement were not offset with increased yield.

At Franklin Co. Field 2, deep band with starter combination fertilizer applications resulted in the lowest net return (Table 4.8). This result is due to low corn yields in 2006 and average across years (Table 4.7). Increase early growth in response to concentrated fertilizer deep band and starter band could shorten time to maturity of corn, therefore reaching maturity during periods of high temperature and low precipitation. Average over rotations at Franklin Co. Field 2 showed to net return response to starter application as in Republic County. Significantly higher net return was established with deep band applications (Table 4.8). The significant effects of treatment on net returns in rotation one was great enough to affect the average over rotations.

In the varying prices and costs analysis, using individual year prices and costs resulted in significant net returns in Field 1 rotation two (Table 4.8). Broadcast and broadcast with starter combination fertilizer applications resulted in significantly lower net returns. Higher application rates with the deep band and deep band with starter combination fertilizer applications were not different. Therefore, increased yields would offset the cost of the additional fertilizer application. Individual prices and costs in 2013 and 2014 lead to increased negative net returns at Field 1 rotation four (Table 4.8). This was due to lower grain prices and higher than average application costs in those years (Table 4.1).

Figure 4.1 shows the corn yield level (above the control treatment) needed to increase the partial net return of the control treatment. Roughly, 0.63 Mg ha^{-1} more corn yield at the Franklin location and 0.75 Mg ha^{-1} more at the Republic location are needed to break even to control net return. This additional yield requirement is due to the costs associated with broadcast and deep band application. The fertilizer applied was not included here only the cost of fertilizer application to corn. The average net return for control plots (no P applied) in Republic County was twice of that in Franklin Co. at $3178 and $1543, respectively. At the Franklin Co. location, it would take less corn yield to increase net return compared to the Republic Co. location. Therefore, you are more likely to see significant net returns as observed here for the Franklin Co. location. Franklin Co. is a dryland production system where P is more than likely not the limiting factor affecting yields. The Republic Co. location is highly productive. Therefore, compared to Franklin Co., higher yields would to be achieved at the Republic Co. location to overcome the input costs.

CONCLUSION

Producers consider agronomic as well as environmental and economic aspects of fertilizer placement when considering tillage and application methods. However, for production under strip tillage system the additional application costs associated with broadcast may be unfavorable. Therefore, producers must consider the costs of fertilizer as well as the cost of application to determine the long-term feasibility for each specific cropping system. Results from this study showed that deep band fertilizer application at the same time of the tillage operation under strip tillage system resulted in lower costs and higher net return. The most consistent agronomic response to fertilizer placement resulted from the use of small amounts of fertilizer P applied at planting (starter). Results from this study showed that starter P fertilizer application may result in the most consistent positive net return over time, however this was consistent only under higher yielding conditions with higher P removal rates by the crop. At the same application rates, deep band applications resulted in the highest net returns in several rotations in Franklin County. However, little differences were found between deep band and broadcast when all treatments received strip-tillage in Republic County. This study provided the economic return for P fertilizer application method under strip tillage system, future economic analysis needed for P fertilizer placement under different tillage systems.

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Table 4. 1. The average price of grain, fertilizer cost, and fertilizer application cost used for analysis of net return. The 10-year average was used for analysis using fix price and cost, and individual year for changing price and costs analysis.

	Year											10-year
Item†	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Average
	- Grain, $\$\ \mathrm{kg}^{-1}$ -											
Corn	0.12	0.16	0.16	0.14	0.19	0.25	0.28	0.18	0.15	0.15	0.15	0.18
Soybean	0.23	0.37	0.34	0.34	0.42	0.44	0.52	0.47	0.35	0.31	0.34	0.39
	- Fertilizer, $\$\ \mathrm{kg}^{-1}$ -											
APP	0.35	0.40	0.72	0.87	0.47	0.74	0.83	0.69	0.67	0.67	0.67	0.64
TSP	0.36	0.46	0.55	0.71	0.56	0.70	0.80	0.77	0.69	0.69	0.69	0.62
UAN	0.27	0.30	0.42	0.39	0.29	0.41	0.43	0.44	0.41	0.41	0.41	0.37
	- - - - - - - - - - - - - - - - - - Application cost, $\$\ \mathrm{ha}^{-1}$ - - - - - - - - - - - - - - - - - -											
Starter	2.84	2.22	3.46	1.48	1.24	2.22	5.19	4.57	3.46	3.46	3.34	3.01
Broadcast	8.65	7.91	9.27	10.13	10.25	10.01	12.23	12.23	12.35	13.34	12.11	10.77
Deep Band	23.47	25.95	31.88	30.39	32.74	32.74	30.39	30.39	36.45	40.28	37.31	31.47

† Grain prices received for corn and soybean in $\$\ \mathrm{kg}^{-1}$ (NASS, 2016); Fertilizer cost in $\$\ \mathrm{kg}^{-1}$ (NASS, 2016) for survey of National averages of APP, ammonium polyphosphate; TSP, triple superphosphate; UAN, urea-ammonium nitrate; Application methods in $\$\ \mathrm{ha}^{-1}$ (Edwards and Johanns, 2016).

Table 4. 2. Yearly total precipitation, and average air maximum and minimum temperatures collected from an automated weather station located within one km from the study.

	Republic County			Franklin County		
Year	Precipitation †	Max Temp‡	Min Temp‡	Precipitation	Max Temp	Min Temp
	mm	- - - - - - - °C - - - - - - -		mm	- - - - - - - °C - - - - - - -	
2006	680	19.8	5.13	812	20.9	7.67
2007	975	18.2	5.32	1271	19.1	7.22
2008	1127	17.0	3.96	1135	17.6	5.67
2009	706	17.7	3.83	1179	17.8	6.57
2010	1442	18.2	6.18	1911	19.5	8.13
2011	523	19.1	5.55	734	20.2	7.88
2012	415	20.9	5.61	536	22.5	8.83
2013	571	17.7	4.46	734	17.9	5.87
2014	482	17.8	4.69	687	18.2	5.96
2015	702	19.3	5.72	962	19.6	7.38
2016	848	21.4	6.00	903	21.6	7.85
Average	762	18.5	5.04	996	19.3	7.12

† Precipitation total by year.

‡ Average maximum and minimum air temperatures measured at 2 m above ground.

Table 4. 3. Statistical significance for the effect of treatment on net return above the control by two-year rotation for Fields 1 and 2 and across fields at the Republic County location. The fixed prices and costs analysis was conducted using the 10-year average for grain price, fertilizer cost, and fertilizer application costs, and the varying prices and costs analysis was conducted with individual years for varying grain prices, fertilizer costs, and fertilizer application costs and average treatment differences over rotations by location.

Rotation†	Year	Fixed	Varying
		- - - - - - - - p > F - - - - - - - -	
		Field 1	
1	2006-2007	0.798	0.402
2	2008-2009	0.028	0.038
3	2010-2011	0.932	0.909
4	2012-2013	0.430	0.473
5	2014-2015	0.249	0.264
Field Average		0.850	0.735
		Field 2	
1	2007-2008	0.452	0.394
2	2009-2010	0.282	0.471
3	2011-2012	0.525	0.533
4	2013-2014	0.127	0.107
5	2015-2016	0.005	0.128
Field Average		0.071	0.099
Location Average		0.490	0.395

† Corn-soybean two-year rotations, field average across two-year rotations, and location average across fields.

Table 4. 4. The effects of fertilizer rate and placement on corn grain and soybean seed yields at the Republic County location (adapted from Chapter 3 and Appendix C).

		10 Kg P ha^{-1}†	20 Kg P ha^{-1}				39 Kg P ha^{-1}					59 Kg P ha^{-1}
Year	Control	ST‡	BC	BC-ST	DB	DB-ST	BC	BC-ST	DB	DB-ST	BC-ST-SY	BC-ST-SY
						Mg ha-1						
						Corn						
2006	11.2	11.7	11.8	12.0	12.1	11.8	12.1	11.9	11.8	11.9	11.1	12.0
2007	11.4c§	13.9b	14.0ab	14.5ab	14.5ab	14.3ab	14.4ab	14.5ab	14.4ab	14.4ab	14.4ab	14.6a
2008	12.0e	14.3abc	13.8cd	14.8a	14.0bcd	14.6ab	13.6d	14.4ab	14.3abc	14.8a	14.4ab	14.3ab
2009	14.0c	16.2ab	16.1ab	17.0a	15.9b	17.0a	16.5ab	16.8a	16.0ab	16.6ab	17.0a	16.7ab
2010	11.8b	13.7a	13.8a	13.7a	14.1a	14.2a	14.0a	14.5a	13.5a	13.7a	14.5a	14.1a
2011	11.2d	13.0c	13.5bc	13.9abc	13.2c	13.8abc	13.7abc	14.3ab	13.8abc	13.8abc	14.6a	13.1c
2012	6.60c	7.80b	7.80b	7.80ab	8.10ab	7.90ab	8.30ab	8.00ab	8.00ab	8.30ab	7.80b	8.80a
2013	6.90g	8.10cde	7.30fg	8.40bcde	7.90ef	9.00ab	8.00def	8.80abc	7.90ef	8.50bcde	9.30a	8.70abcd
2014	10.0e	12.5a	10.8de	12.1abc	11.1cde	11.8abcd	11.6abcd	12.4ab	11.3bcd	12.2ab	11.8abcd	12.7a
2015	11.3c	13.9b	14.0ab	14.7ab	12.3c	14.5ab	14.4ab	14.8ab	13.8b	14.8ab	15.3a	13.7b
Average	10.5e	12.4cd	12.2d	12.8ab	12.3d	12.8ab	12.7abc	13.1a	12.5bcd	13.0a	13.1a	13.0a
						Soybean						
2006	3.0d	3.2bcd	3.3b	3.4ab	3.3bc	3.3bc	3.2bcd	3.6a	3.0cd	3.2bc	3.3ab	3.3ab
2007	3.5e	4.1cd	4.2cd	4.2c	4.1cd	4.1cd	4.2cd	4.4b	4.2cd	4.1d	4.4b	4.7a
2008	4.1bc	4.1bc	4.2bc	4.0c	4.3ab	4.1bc	4.3ab	4.0c	4.3ab	4.3ab	4.2bc	4.5a
2009	4.0f	4.0ef	4.3cd	4.2def	4.3cde	4.5c	4.8ab	4.4cd	3.9f	4.6bc	4.6bc	4.9a
2010	3.3c	4.2ab	4.1b	4.3ab	4.2ab	4.3ab	4.2ab	4.6ab	4.2ab	4.0b	4.7a	4.3ab
2011	3.7d	4.1c	4.2bc	4.2bc	4.3bc	4.4ab	4.7a	4.4ab	4.1bc	4.3bc	4.3bc	4.7a
2012	3.2d	3.9c	3.8c	4.0bc	4.0bc	4.0bc	4.1bc	4.2ab	4.1abc	4.1abc	4.5a	4.1abc
2013	2.6e	3.1cd	3.0d	3.2abcd	3.3abcd	3.1cd	3.4ab	3.1cd	3.3abcd	3.1bcd	3.3abc	3.5a
2014	4.9c	5.6b	5.6b	6.0ab	5.9ab	6.0ab	5.9ab	6.1ab	5.8b	6.1ab	6.4a	6.4a
2015	3.8d	4.3c	4.5bc	4.6abc	4.6abc	4.4bc	4.6abc	4.8ab	4.4c	4.6abc	4.6abc	5.0a
Average	3.5g	4.0f	4.1ef	4.2de	4.2de	4.2de	4.3bcd	4.4bc	4.1ef	4.3cd	4.5ab	4.6a

† Rate of total phosphorus (P) fertilizer (kg P ha^{-1}) applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer ST, starter band at planting; BC, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, broadcast application of 20 kg P ha^{-1} before soybean.

§ Different letters in rows by year indicate significant differences (*$p<0.10$*).

Table 4. 5. Partial net return as a percent of the control treatment for each two-year rotation at Republic County Field 1 and Field 2. The fixed prices and costs analysis was conducted using the 10-year average for grain price, fertilizer and fertilizer application costs. The varying prices and costs analysis was conducted with individual years for varying grain prices, fertilizer costs, and fertilizer application costs and average treatment differences over rotations by location.

Treatment		Field 1						Field 2						Location
Rate†	Placement‡	1§	2	3	4	5	Average	1	2	3	4	5	Average	Average
kg ha^{-1}		- % of control -												
							Fixed prices and costs							
10	ST	6.2	12.1abc¶	8.4	16.8	19.3	13.2	12.4	17.6	19.9	15.5	13.7bcd	16.0cde	14.6
20	BC	6.3	11.5abc	9.8	14.4	10.3	11.0	13.5	14.7	20.3	8.9	14.6abcd	14.5e	12.8
20	BC-ST	7.6	14.3abc	9.5	17.4	19.1	14.1	13.0	21.2	25.6	19.6	21.2ab	20.2abc	17.1
20	DB	8.2	13.1abc	13.7	24.4	14.7	15.4	18.0	15.5	22.9	17.5	7.1d	16.2cde	15.8
20	DB-ST	5.7	17.2ab	14.3	18.0	15.2	14.7	14.0	22.0	26.2	23.3	19.8abc	21.1ab	17.9
39	BC	6.2	12.8abc	14.0	22.9	13.9	14.8	13.7	15.3	22.7	14.2	18.6abc	17.0bcde	15.9
39	BC-ST	7.5	12.8abc	12.9	14.5	20.8	14.7	11.0	21.3	29.2	20.5	20.1abc	20.5abc	17.6
39	DB	6.4	8.6c	6.0	20.8	11.3	11.9	16.4	15.6	26.8	14.8	14.0bcd	17.7bcde	14.8
39	DB-ST	4.6	17.2a	9.1	18.8	18.0	15.2	14.6	14.7	25.1	21.3	21.0ab	19.6bcde	17.4
39	BC-ST-SY	-1.1	11.2bc	9.4	13.8	13.6	11.6	10.2	20.7	32.5	26.9	22.7a	23.0a	17.3
59	BC-ST-SY	6.0	13.3abc	9.7	20.6	19.1	16.8	12.4	12.6	16.0	20.8	11.0cd	15.2de	16.0
							Varying prices and costs							
10	ST	8.1	11.9ab	8.8	16.7	19.4	13.5	12.7	18.3	19.9	15.4bcd	15.8	16.6cde	15.1
20	BC	8.3	11.6ab	10.1	14.7	9.6	11.4	13.8	14.9	20.6	8.1d	16.4	14.8e	13.1
20	BC-ST	9.7	14.1ab	10.1	17.3	18.6	14.5	13.5	21.3	25.9	19.0abc	24.3	20.9abcd	17.7
20	DB	10.0	13.0ab	14.1	23.8	14.7	15.7	18.4	15.8	22.7	17.5abc	20.7	19.1abcde	17.4
20	DB-ST	7.7	16.9a	14.9	17.8	15.0	15.1	14.6	22.0	26.3	23.4ab	23.0	21.9ab	18.5
39	BC	8.7	13.0a	14.8	22.9	12.6	15.2	14.3	15.1	23.3	12.8cd	20.6	17.3bcde	16.2
39	BC-ST	10.9	12.6ab	13.8	15.0	19.5	15.3	11.8	21.8	29.9	19.4abc	22.3	21.1abc	18.2
39	DB	9.3	8.2b	6.7	19.9	11.2	12.3	17.5	15.0	26.8	14.9bcd	16.2	18.2bcde	15.3
39	DB-ST	7.2	16.7a	10.2	18.7	17.7	15.8	15.7	12.9	25.3	21.3abc	24.2	20.1abcd	17.9
39	BC-ST-SY	3.1	10.5ab	10.3	13.7	12.0	12.1	11.0	21.3	32.9	26.2a	24.2	23.5a	17.8
59	BC-ST-SY	13.0	11.7ab	11.6	21.2	16.9	17.8	13.9	16.2	17.0	19.3abc	9.9	15.9de	16.9

† Rate of total phosphorus (P) fertilizer (kg P ha^{-1}) applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer ST, starter band at planting; BC, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast application of 20 kg P ha^{-1}.

§ Rotations correspond to corn-soybean in 2007-2008, 2009-2010, 2011-2012, 2013-2014, 2015-2016, and average at Field 2 and 2006-2007, 2008-2009, 2010-2011, 2012-2013, 2014-2015, and average at Field 1.

¶ Different letters in rows by year indicate significant differences (*p<0.10)*.

Table 4. 6. Statistical significance for the effect of treatment on net return above the control by two-year rotation for Fields 1 and 2 and across fields at the Franklin County location. The fixed prices and costs analysis was conducted using the 10-year average for grain price, fertilizer costs, and fertilizer application costs and the varying prices and costs analysis was conducted with individual years for varying grain prices, fertilizer cost, and fertilizer application costs and average treatment differences over rotation by location.

Rotation†	Year	Fixed	Varying
		- - - - - - - - p > F	- - - - - - - -
		Field 1	
1	2007-2008	0.348	0.375
2	2009-2010	0.001	0.001
3	2011-2012	0.326	0.333
4	2013-2014	0.053	0.008
5	2015-2016	0.779	0.598
Field Average		0.071	0.053
		Field 2	
1	2006-2007	0.033	0.037
2	2008-2009	0.201	0.097
3	2010-2011	0.656	0.682
4	2012-2013	0.420	0.595
5	2014-2015	0.224	0.201
Field Average		0.002	0.001
Location Average		0.001	0.001

† Corn-soybean two-year rotations, field average across two-year rotations, and location average across fields.

Table 4. 7. The effects of fertilizer rate and placement on corn grain and soybean seed yields at the Franklin County location (adapted from Chapter 3 and Appendix C).

		10 Kg P ha^{-1}†	20 Kg P ha^{-1}				39 Kg P ha^{-1}					59 Kg P ha^{-1}
Year	Control	ST‡	BC	BC-ST	DB	DB-ST	BC	BC-ST	DB	DB-ST	BC-ST-SY	BC-ST-SY
		- Mg ha-1 -										
						Corn						
2006	5.1f§	5.3ef	6.0abcd	5.8bcde	6.1abc	6.4ab	6.3ab	6.3ab	6.4a	5.6def	5.7cde	6.5a
2007	5.9	6.4	6.0	6.5	6.5	6.6	6.2	6.5	6.5	6.3	6.4	6.4
2008	8.2	8.9	8.9	9.6	9.4	8.8	9.0	9.0	8.4	8.7	8.7	9.3
2009	8.7de	8.8de	8.9bcde	8.9cde	9.6a	8.9bcde	9.4abc	9.3abcd	9.0cde	8.7e	9.5ab	9.7e
2010	5.5b	5.6b	6.2a	6.4a	6.4a	6.7a	6.3a	6.3a	6.4a	6.2a	6.4a	6.5a
2011	4.5	4.8	4.9	5.0	4.7	5.3	5.3	5.5	5.4	5.2	5.0	5.2
2012	0.7	0.7	0.9	0.9	0.9	0.7	0.8	0.7	0.8	0.9	0.7	0.9
2013	6.1	6.0	5.4	5.8	5.7	5.3	4.9	4.5	4.8	4.5	4.5	4.6
2014	7.2abc	6.2bcd	7.4ab	6.2bcd	5.8cd	7.1abc	7.8a	7.3ab	7.6ab	5.1d	5.3d	6.6abcd
2015	8.2e	90d	9.4bcd	9.6abc	9.5abc	9.2cd	9.9a	9.9a	9.8ab	9.8a	9.6abc	9.8a
Average	5.9d	6.1bcd	6.3abc	6.4abc	6.4abc	6.4abc	6.5a	6.4ab	6.4ab	6.0cd	6.1abcd	6.4abc
						Soybean						
2006	2.9	3.0	3.0	3.0	2.8	2.9	2.8	3.0	2.8	3.0	2.9	3.0
2007	1.3	1.3	1.4	1.3	1.3	1.4	1.3	1.4	1.5	0.9	1.3	1.3
2008	2.9	3.3	3.2	3.1	3.1	3.2	3.1	3.3	3.3	3.2	3.1	3.4
2009	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
2010	2.0c	2.3a	2.3a	2.2bc	2.2ab	2.2ab	2.2ab	2.3ab	2.3ab	2.3ab	2.2ab	2.3a
2011	4.4	4.5	4.8	4.9	4.7	5.2	5.0	5.1	5.2	4.7	4.8	4.9
2012	3.9e	4.2de	4.2cd	3.4bcd	4.3cd	4.7ab	4.4bcd	4.6abc	4.8a	4.6abc	4.3bcd	4.8a
2013	2.7	2.6	2.7	2.7	2.9	2.8	2.9	2.9	3.0	2.8	2.8	2.9
2014	2.2c	2.5ab	2.4bc	2.6a	2.5ab	2.7a	2.6a	2.6a	2.6a	2.7a	2.6ab	2.6a
2015	3.9b	3.9b	4.3a	4.2ab	4.2ab	4.2a	4.3a	4.4a	4.5a	4.3a	4.2ab	4.5a
Average	3.0c	3.1b	3.2ab	3.2ab	3.2b	3.3ab	3.2ab	3.3ab	3.3a	3.2b	3.1b	3.3ab

† Rate of total phosphorus (P) fertilizer (kg P ha^{-1}) applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer ST, starter band at planting; BC, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast application of 20 kg P ha^{-1}.

§ Different letters in rows by year indicate significant differences (*$p<0.10$*).

Table 4. 8. Partial net return as a percent of the control treatment for each two-year rotation at Franklin Co. Field 1 and Field 2. The fixed prices and costs analysis was conducted using the 10-year average for grain price, fertilizer and fertilizer application costs. The varying prices and costs analysis was conducted with individual years for varying grain prices, fertilizer costs, and fertilizer application costs and average treatment differences over rotations by location.

Treatment		Field 1						Field 2						Location
Rate†	Placement‡	1§	2	3	4	5	Average	1	2	3	4	5	Average	Average
kg ha^{-1}		- % of control -												
Fixed prices and costs														
10	ST	16.9	5.4ab¶	6.4	3.3abc	5.7	5.5abcd	3.8bc	4.1	4.3	-6.9	-8.9	-1.9cd	1.8cd
20	BC	6.8	4.8b	9.3	-7.7bc	2.4	1.6bcd	17.4ab	3.1	11.5	-4.3	5.8	6.2abc	3.9bcd
20	BC-ST	9.8	0.2bc	14.9	11.5abc	5.3	7.1abc	6.2bc	8.0	12.2	-5.5	-6.1	2.7bcd	4.9bc
20	DB	13.3	11.5a	9.7	12.2abc	6.1	9.5ab	19.9ab	9.3	11.6	12.9	-7.4	9.1ab	9.3ab
20	DB-ST	13.0	2.9bc	26.6	15.6a	8.2	12.4a	25.4a	2.7	22.4	-1.9	3.3	10.2ab	11.3a
39	BC	3.5	3.0bc	13.9	-2.7abc	2.2	3.2bcd	7.7bc	1.1	11.0	-4.6	7.0	4.3bc	3.8bc
39	BC-ST	10.6	2.5bc	19.1	-7.7c	2.1	4.7abcd	14.7ab	-0.1	12.5	-10.2	4.0	4.0bc	4.3bc
39	DB	13.8	3.2bc	28.0	12.4ab	6.9	12.3a	27.6a	-1.4	20.1	14.0	11.1	14.0a	13.2a
39	DB-ST	7.9	-0.1b	17.1	7.8abc	8.0	7.8abc	2.9bc	0.1	6.9	2.5	-13.2	-0.5cd	3.6bcd
39	BC-ST-SY	-4.3	2.4c	6.7	-8.9c	1.5	-1.6d	-6.4d	-3.5	3.7	-19.6	-17.7	-11.6e	-6.6e
59	BC-ST-SY	0.6	-9.4d	15.0	-5.5abc	-0.2	0.3cd	-2.2cd	-6.4	5.2	-17.1	-4.7	-5.5de	-2.6de
Varying prices and costs														
10	ST	17.2	6.3ab	6.4	0abcd	4.4	4.0abcd	4.3bcd	3.7 abc	4.8	-7.0	-10.4	-2.1de	1.0de
20	BC	7.3	5.5ab	9.5	-14.5bcde	0.9	-0.6bcd	17.5ab	7.9 abc	11.3	-2.9	5.0	6.3abcd	2.9cd
20	BC-ST	10.8	-0.9c	14.8	10.4abc	3.5	5.8abc	6.2bcd	9.6 ab	12.4	-3.6	-8.1	2.7bcde	4.3bcd
20	DB	14.1	10.3a	9.3	15.8a	4.9	9.3ab	19.4ab	2.0 a	11.2	11.7	-8.5	8.5abc	2.9abc
20	DB-ST	14.0	1.8bc	25.5	18.0a	6.7	11.8a	25.2a	2.0 abc	21.8	-2.6	2.8	9.7ab	10.8ab
39	BC	4.8	1.2bc	14.4	-15.0cde	0.01	-0.1bcd	7.5bc	1.2 abc	11.4	-4.0	5.3	4.1bcd	2.0d
39	BC-ST	12.1	0.6bc	19.4	-21.5cde	-0.01	1.1bcd	16.5ab	-0.7 bcd	13.2	-10.3	2.0	3.9bcd	2.5cd
39	DB	15.9	0.5bc	26.7	14.5ab	5.4	11.7a	29.6a	-2.4 cd	20.0	11.3	11.7	13.8a	12.8a
39	DB-ST	10.3	-2.7c	16.8	6.7abc	6.2	6.8ab	7.5bc	-1.2 bcd	7.9	1.4	-15.7	-0.4cde	3.2cd
39	BC-ST-SY	-2.3	-5.3c	7.6	-23.3de	0.2	-5.1d	-11.9d	-8.7 d	4.8	-17.6	-22.6	-11.8f	-8.4f
59	BC-ST-SY	3.8	-13.1d	15.9	-24.1e	-2.0	-4.0cd	-3.2cd	-5.8 cd	7.4	-14.3	-9.4	-5.8ef	-4.9ef

† Rate of total phosphorus (P) fertilizer applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer Control, no fertilizer applied; ST, starter band at planting; BC, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast of 20 kg P ha^{-1} before planting.

§ Rotations correspond to corn-soybean in 2007-2008, 2009-2010, 2011-2012, 2013-2014, 2015-2016, and average at Field 1 and 2006-2007, 2008-2009, 2010-2011, 2012-2013, 2014-2015, and average at Field 2.

¶ Different letters in columns are significant (*p<0.10*).

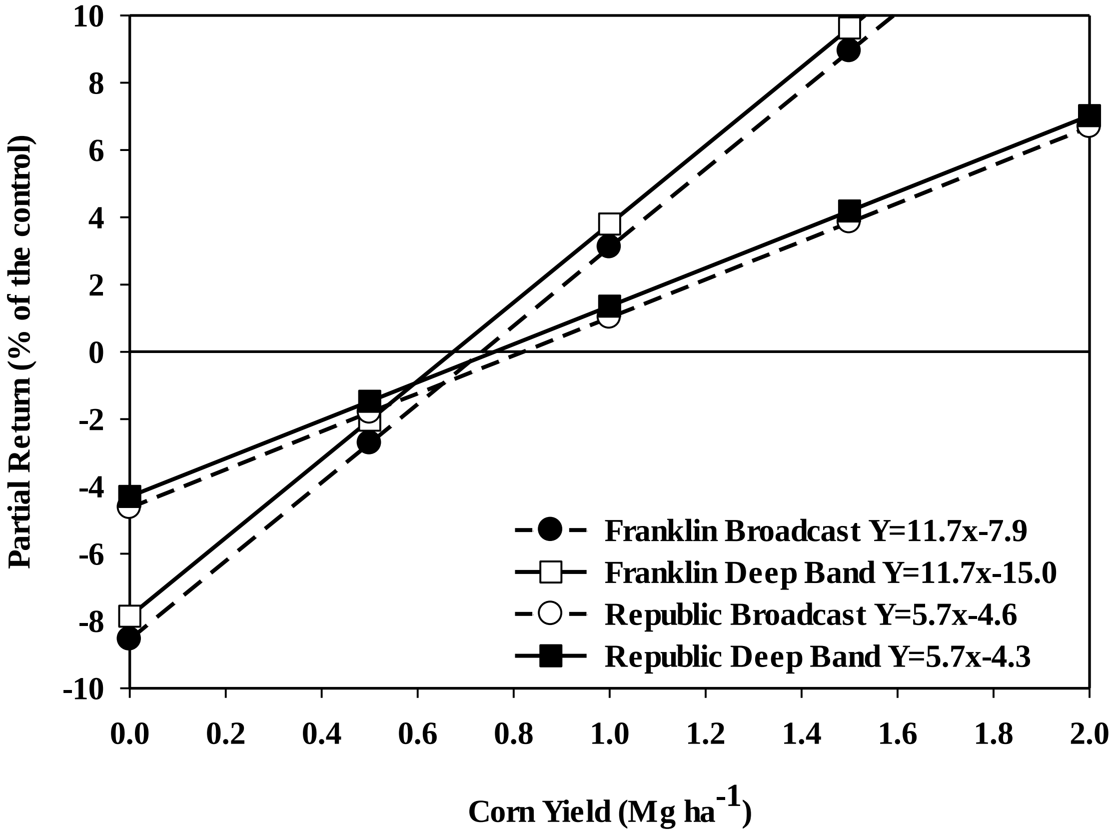

Figure 4. 1, Corn yield required above the control treatment to increase net return (percent of the control) for Republic and Franklin counties. Data points represent the additional corn yield needed to offset broadcast and deep band application costs in relation to the net return of the control treatment.

Chapter 5 - Evaluating the interaction between chelated Fe fertilizer sources and placement on soybean

ABSTRACT

Chelated micronutrient fertilizers provide flexibility for application in combination with other fertilizer sources, however, little research has been conducted evaluating sources and placement for soybean (*Glycine Max* L.). The objective of this study was to evaluate three commercially available chelated iron (Fe) fertilizer sources and two placement methods for soybean. The study was conducted at six locations in 2014 and 2015. The experimental design was a randomized complete-block with four replications. Two placement methods and four fertilizer treatments were arranged as complete factorial. The fertilizer sources were 1) phosphorus (P) only using (0-16-19); 2) ethylenediamine tetraaceticacid-Fe (EDTA+P); 3) hydroxyethyl ethylenediamine triaceticacid-Fe (HEDTA+P), and 4) glucoheptonate- Fe (GCH+P). Fertilizer treatments were applied in-furrow in contact with the seed and as surface dribble over the row at planting. Results showed chelate fertilizer sources effected early biomass, with less effect from fertilizer placement. In-furrow applications resulted in greater concentrations of P in the tissue at the V4 growth stage but not in uptake. Both EDTA+P and HEDTA+P resulted in greater concentrations and uptake of Fe and lower Mn uptake. However, the application of GCH+P had no negative effect on Mn uptake compared to EDTA+P and HEDTA+P. Across locations, EDTA+P and HEDTA+P showed higher yield than GCH+P. However, chelate rates may need adjusting for yield responses.

Keywords: chelating agent, soybean, in-furrow, EDTA, HEDTA, glucoheptonate.

INTRODUCTION

Plants have two main strategies for improving acquisition of Fe nutrients. Strategy I plants, such as soybeans, acidify the rhizosphere by releasing protons, enhancing the reduction of Fe(III) to Fe(II) (Marschner and Romheld, 1994). Strategy II plants produce specific chelating agents that complex Fe(III) and take up through a highly specific uptake systems. Increasing yield with the application of synthetic chelated micronutrients has been studied extensively since the 1920's. Depending on the chemical composition, chelating agents can have greater specificity for Fe(III). Two main types of chelates used in agriculture are acids and sugars. Both EDTA and HEDTA are considered acids and carry a net negative charge in solution (Clemmons et al., 1990). Glucoheptonates are sugar based compounds that utilize carboxyl groups for chelating metals (Clemmons et al., 1990).

Chelating agents are used extensively in the Great Plains and North Central regions due to widespread Fe deficiency in soybean (Goos and Johnson, 2000). The probability of increasing soybean yield with the application of micronutrients is highest with Fe (Liesch et al., 2011) and Mn (Loecker et al., 2010) when compared to other nutrients. However, yield responses from chelate application is highly variable. Research has shown more consistent responses to chelate application with seed treatment or in-furrow application in contact with the seed (Penas et al., 1990; Liesch et al., 2012; Wiersma, 2005). Lack of crop response to chelate fertilizers could be attributed to low application rates (Goos and Johnson, 2000). Penas et al., (1990) studied in-furrow applied Fe chelate fertilizer solutions and reported that rates as high as 4.5 kg Fe-EDDHA ha^{-1} may be needed to be applied to achieve maximum yield. These rates may not be economical depending on soybean prices.

Soil application of chelated Fe fertilizers have shown to decrease Mn uptake in soybean potentially leading to Mn deficiency symptoms (Ghasemi-Fasaei et al., 2003). Therefore, chelated Mn fertilizer sources are typically not recommended for soybean. Oliver and Barber (1966) reported diffusion was the most important mechanism for movement of Fe, Mn, and Zn to soybean roots. Previous studies showed that high concentrations of P can influence soybean response to these metals (DeMooy et al., 1973). Excessive P fertilization can reduce the availability of Zn (Burleson et al., 1961) and Fe (Brown, 1961) by precipitating and immobilizing metals within the plant and soil. In addition to the effect of chelated Fe on other metals, there is potential for an effect on plant P uptake. A soil incubation study evaluating the effect of chelates on water soluble P, determined using the molybdate blue method (Murphy and Riley, 1962), resulted in increased P with the application of EDTA-Fe and HEDTA-Fe (Edwards et al., 2016a). However, in a greenhouse study that evaluated the EDTA-Fe and HEDTA-Fe, there were inconsistent responses in corn uptake of P (Edwards et al., 2016b). Increasing chelated fertilizer application rate was also found to increase Mehlich-1 extractable P (Maguire and Heckendorn, 2011) and Mehlich-3 extractable P (Mehlich, 1984) for EDTA-Fe and HEDTA-Fe in a soil with high P adsorption capacity. This increase in P was attributed to EDTA-Fe binding Fe within soil colloids and decreasing the P adsorption capacity of the soil (van der Zee and van Riemsdijk, 1988).

Chelated micronutrient fertilizers are typically applied in combination with other fertilizer sources (particularly P and K). However, little research has been conducted under field conditions to evaluate the effect of chelates on phosphorus uptake and concentrations in soybean. A continuation of the soil incubation and greenhouse studies listed above are needed in a field setting. By looking at various application methods, higher rates of chelated Fe fertilizer sources can be applied (i.e. on the soil surface). The objectives of this study were to evaluate the interaction of chelated Fe fertilizer and placement on P, Fe, Mn, and Zn in soybean.

MATERIALS AND METHODS

As stated above, this study was established as a continuation of previous research looking at the effects of chelated Fe fertilizer source on P in various soil types. The study was conducted on six locations in Kansas in 2014 and 2015. Planting dates, cultivar, population, and soil analysis are listed in Table 5.1. Yearly total precipitation and maximum and minimum temperatures for each location are given in Table 5.2.

The experimental design was a complete randomized block design with four replications. The treatment structure included two placement methods and four fertilizer sources in a complete factorial arrangement. Placement methods included in-furrow and dribbled on the surface at planting. Fertilizer sources included a P-K only treatment and three chelated Fe fertilizers applied in combination with P-K fertilizer (EDTA+P, HEDTA+P, GCH+P). Phosphorus and potassium fertilizer 0-16-19 ($N-P_2O_5-K_2O$) at 102 l ha^{-1} supplying 9 kg P ha^{-1} and 49 kg K ha^{-1} for all treatments. Treatments consisted of chelated Fe fertilizer mixed with 0-16-19 and applied at the same time in-furrow and surface band. Chelated Fe fertilizers were applied at 28.2 and 56.1 l ha^{-1} rates for in-furrow and surface band, respectively. With applications in-furrow and surface banding, a volume of 187 l ha^{-1} was used. Both the EDTA-Fe and HEDTA-Fe fertilizers were liquid with 45 g Fe kg^{-1}. The glucoheptonate- Fe fertilizer source was a commercial CeeQuest N5Fe-758 (EnCee Chemical, New Bern, North Carolina). The study plots were 3.0 m wide (four soybean rows planted on 76 cm spacing) by 7.6-9.1 m long for all locations.

Initial soil samples were collected in spring prior to soybean planting by collecting one composite sample of 12 individual cores taken at random to get a representative sample at 15 cm sampling deep per plot and averaged over location. Samples were analyzed for soil pH in a 1:1 (soil:water). Mehlich-3 soil test P (STP) was determined colorimetrically (Frank et al., 1988). Ammonium acetate potassium (K) was determined by ICP-OES (Inductively coupled plasma optical emission spectrometry) (Warncke and Brown, 1998). Walkley-Black organic matter was determined using methods outlined by Combs and Nathan (1998).

Ten whole plant samples were collected at the V-4 growth stage and thirty soybean trifoliate (uppermost fully developed trifoliate without the petiole) samples were collected at the R3 growth stage (Pedersen, 2009). Plant tissue samples were dried in a forced air oven at 60 degree Celsius for a minimum of 4 days. After drying, plant samples were ground with a Wiley Mill grinder to pass a 2 mm screen. Two separate digests were conducted on plant tissue. A sulfuric acid and hydrogen peroxide digest was performed following Thomas et al. (1967) and analyzed for P. A nitric perchloric digest (Self and Rodriguez, 1999) was used and samples were analyzed for Fe, Mn, and Zn by inductively coupled plasma atomic emission spectroscopy (ICP-AES).

The center two rows of soybeans were machine harvested for the total length of the plot. Grain weight were recorded at the end of the growing season and adjusted for 130 g kg-1 moisture. Soybean seed grain moisture and test weight were recorded. The seed grain was then ground using a coffee grinder and analyzed for total P (Thomas et al., 1967), Fe, Mn, and Zn concentration (Self and Rodriguez, 1999).

Data were analyzed both by location and across locations using *proc Glimmix* in SAS 9,4 (SAS, 2015) with block as a random factor. For the analysis across location, both location and block within location were considered as random factors. When the fertilizer source and fertilizer placement interaction was significant, main effect test were ignored and main effect tests were tested between fertilizer source and fertilizer placement. When the fertilizer source and fertilizer placement interaction was not significant, main effect tests using least squared means were used to interpret those significant main effects. Statistical significance was determined ($p<0.10$).

RESULTS AND DISCUSSION

Based on initial soil samples taken in the spring before soybean planting (Table 5.1), all locations, except Location 4, can be considered low in soil test P (STP) (Liekam et al., 2003). The same rates of P were still applied at 9 kg P ha^{-1} for all treatments. Soybean cultivars, population, and planting dates were all typical for each location. Yearly total precipitation, and maximum and minimum temperatures for each location are listed in Table 5.2.

Whole plant samples taken at V-4 were used to measure early growth biomass (Table 5.3). Fertilizer placement showed no influence on early biomass at any location. However, chelated Fe fertilizer source showed significant increase in soybean growth at Location 5 in 2015. Both EDTA+P and HEDTA+P applications resulted in greater biomass compared to P-only and GCH+P. A significant interaction between placement and source at location 4 resulting in significantly lower biomass with GCH+P in-furrow applications (Table 5.3).

Macronutrients

Previous research has shown chelated Fe fertilizer sources can have a positive effect on P availability (Edwards et al., 2016a; Edwards et al., 2016b). In-furrow applications were found to increase P concentrations at Location 1 and Location 2 in 2014, but not P uptake (Table 5.4). Chelated Fe fertilizer addition to P fertilizer had no effect on P concentration or uptake at the V-4 growth stage. Greater plant biomass and increased P concentrations did not influence P uptake. Applying the fertilizer in-furrow did increase P uptake at Location 3 (Table 5.4). However, twice the chelate application rate was required as a surface band to increase P uptake at Location 5 in 2015. Higher application rates have been shown to increase plant available P (Edwards et al., 2016a) but studies have shown inconsistent responses with P uptake following chelate application. It is possible that even higher chelate rates would be required to see a response in P uptake, but those rates may not be economical. Greater P uptake with in-furrow applications in Location 3 continued into greater concentrations in trifoliate tissue at R-3 and grain following harvest (Table 5.5). As with early biomass, P concentrations, and P uptake, chelated Fe source had no effect on P concentrations in trifoliates or in grain.

Micronutrients

Chelates have specific affinities for Fe. It is well known that HEDTA and EDTA have greater specificities for Fe than most other chelates (Lindsay, 1979), therefore keeping Fe soluble for uptake. Glucoheptonate chelates have shown to have higher stability constants with Fe compared to EDTA and HEDTA (Clemons et al., 1990; Lindsay, 1979). However, due to the biodegradability of sugar compounds such as glucoheptonates can lead to decreased time Fe is chelated. Glucoheptonate products were originally developed for their use in alkaline conditions. In this study, there were no differences in early concentrations or uptake of Fe (Table 5.6). Greater Fe concentrations in trifoliates in Republic and in grain at Location 1 in 2014 with EDTA applications (Table 5.7). Continuous Fe uptake is required throughout the growing season (Burton et al, 1998; Karlen et al., 1982) and based on these results EDTA would be the chelate to choose for applications. The rates of chelate might need to be adjusted to ensure greater uptake throughout the growing season as twice the chelate rate applied on the soil surface resulted in no difference in Fe trifoliate concentration than in-furrow at Location 6 (Table 5.7). No critical level for Fe concentrations in seed have been determined (Wiersma, 2005). Chelate Fe fertilizer application has been found to increase yield, however have little to no effects on seed Fe concentration (Wiersma, 2005).

The antagonistic effect of chelated Fe fertilizer on Mn uptake is well documented (Ghasemi-Fasaei et al., 2003). Previous studies have found that when chelated Fe fertilizer is applied to soil, a decrease in Mn uptake and Mn in leaves occurs (Heenan and Campbell, 1983; Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011). However, little research has been conducted evaluating glucoheptonate products as a possible Fe source without adverse effects on Mn. Chelated fertilizer sources are chosen based on their stability constants with the metal ions being applied. The chelate EDTA has a higher stability constant with Fe and Mn compared to HEDTA at lower pH (Lindsay, 1979). Glucoheptonate chelated fertilizers were originally developed for use in higher pH conditions (Clemons et al., 1990). At higher pH, Fe availability would not be an issue and chelated Fe fertilizer may not be necessary. However, glucoheptonate product applications may still prove beneficial have not yet been tested.

At all locations, there was no difference between Mn concentrations with GCH+P applications compared to P-only (Table 5.8). Since there were few locations where Fe concentrations were affected by chelate source, GCH would be a suitable source of Fe without the adverse effects on Mn concentrations. Early concentrations of Mn was only affect by placement at one location, location 4, and uptake of Mn at V-4 was not affect by placement (Table 5.8). However, significantly lower Mn concentrations were observed with EDTA+P and HEDTA+P applications in-furrow and surface banded at all locations and lower uptake at most locations. Therefore, both EDTA and HEDTA would not be suitable chelates. As with Fe concentrations, similar tends were observed with significant Mn concentrations and uptake translated into greater trifoliate tissue and grain concentrations (Table 5.9). Significantly lower Mn concentrations in R3 trifoliates and grain occurred with EDTA+P and HEDTA+P application. However, these values are near critical levels for Mn concentration in trifoliate (Cox, 1968; Ohki, 1976; Ohki et al., 1977; Wilson et al., 1982; Bell et al., 1995). Therefore, applications of EDTA and HEDTA could induce manganese deficiency. Within this study, there were no physical signs of Mn deficiency at any locaitons. There was also no significant effect of the addition of GCH to P-K fertilizer. Therefore, as with early Mn concentration and Mn uptake, GCH may be a preferred chelate over EDTA-Fe and HEDTA-Fe. A significant interaction for Mn concentrations in trifoliate and grain concentrations show that in-furrow applications of GCH+P would be the superior placement at the majority of the locations (Table 5.9).

Even though chelated Fe fertilizers can have a negative effect on Mn, research has shown no negative effects on other metals such as Zn (Romizadeh and Karimian, 1996; Ghasemi-Fasaei et al., 2003). Glucoheptonate chelates are known to have lower stability constants for Zn compared to EDTA and HEDTA (Lindsay, 1979), therefore chelates such as EDTA and HEDTA could potentially increase Zn solubility and plant availability more than GCH. Surface applied chelate fertilizers at twice the rate of in-furrow increased Zn concentrations at Republic in 2014 and Thomas in 2015 and increased Zn uptake at V-4 (Table 5.10). However, higher Zn concentrations were achieved with in-furrow applications at Location 6 even though both locations had the same soil type. Mixed results were observed with greater Zn uptake with surface applied chelates at Location 1 in 2014 and Location 4 in 2015, yet lower uptake at Location 2 in 2014 and Location 6 in 2015. When comparing source, P-only and GCH+P generally resulted in lower Zn concentrations and uptake in V-4 tissue (Table 5.10). When looking at the interaction of placement and source, higher concentrations were achieved with EDTA+P and HEDTA+P in-furrow and HEDTA+P surface banded were the superior treatments. As for chelated fertilizer application, GCH generally resulted in lower concentrations and lower uptake rates.

In-furrow applications resulted in great Zn in trifoliate and grain at Location 5 in 2015 (Table 5.11). Significantly higher Zn concentrations and did not necessarily translate into higher concentrations in trifoliate tissue or grain. The critical level for Zn concentration in trifoliate tissue has been determined to be 34 mg Zn kg^{-1} (Hitsuda et al., 2010). There were five locations in this study were trifoliate concentrations were below this critical level. Critical levels for Zn concentrations in seed was found to be 43 mg Zn kg^{-1} (Rashid and Fox, 1992). Other studies have shown little differences in seed Zn concentrations (Moraghan and Helms, 2005; Wiersma, 2012). However, soybean varieties have been found to differ in efficiency of Zn absorption and therefore, could explain the lack of response in increase in Zn concentration (Hartwig et al., 1991). In this study, Zn concentrations in seed ranged from 31.9 to 45.3 depending on the variety grown. Using the critical level set my Rashid and Fox (1992), five locations would result in below critical level Zn concentrations.

Soybean yield

Previous research has shown mixed results for yield responses to chelate application. In this study, in-furrow applications only increased yield at Location 3 and surface applications increased yield at locations 4, 5 and 6 in 2015 (Table 5.12). When comparing chelating agents, GCH applications resulted in lower yields at Location 1 and Location 2 in 2014 with no yield differences in 2015. At Location 2 in 2014, in-furrow and surface applications of GCH+P resulted in the lowest yields. Surface applied chelating agents at twice the chelate rate as in-furrow did result in increased yield as potentially hypothesized. When comparing fertilizer source effects on soybean yield, applications of GCH+P resulted in lower yields compared to other chelates when averaged over locations. There were no differences between EDTA+P and HEDTA+P and the P-only treatment. Therefore, EDTA-Fe and HEDTA-Fe would be a better choice for chelated Fe over GCH.

CONCLUSION

The cost of chelated micronutrient products can play a big role in the decision to apply. Historically, chelated Fe fertilizer application were not economical. However, in areas that are prone to Fe deficiency in soybean, application method, rate, and source should be considered for potential economical return. A glucoheptonate based chelated Fe fertilizer has shown no adverse effects on Mn uptake like other chelates, such as EDTA and HEDTA, and be a comparable Fe source. Previous research has not documented the effect these chelates have on other nutrients in a field environment. Chelates studied here show potential for increasing the uptake of other nutrients.

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Table 5. 1. Soybean cultivar, planting date, and soil information for each location in 2014 and 2015.

				Soil†								
Location	County	Lat, Long.	Year	Series	Subgroup	pH	P	K	OM	Cultivar	Population	Planting Date
							mg kg^{-1}		g kg^{-1}		(plants ha^{-1}) ×1000	
1	Reno	37°57′52″N; 98°4′53″ W	2014	Shellabarger	Udic Argiustoll	6.9	19	183	23	Channel A1016281	445	13-Jun
2	Shawnee	39°7′21″N; 95°55′48″ W	2014	Kimo	Fluvaquentic Hapludoll	7.1	17	218	21	New King 39U2	346	14-Jun
3	Republic	39°46′23″N; 97°47′19″ W	2014	Crete	Pachic Argiustoll	6.2	6	508	28	New King 536 B6	395	21-May
4	Thomas	39°23′15″N; 101°4′36″ W	2015	Keith	Aridic Argiustoll	7.4	27	832	20	Fontanelle 29N04	494	24-Jun
5	Shawnee	39°7′21″N; 95°55′48″ W	2015	Eudora	Fluventic Hapludoll	7.2	20	256	20	Stine 42RE02	346	19-Jun
6	Republic	39°46′23″N; 97°47′19″ W	2015	Crete	Pachic Argiustoll	6.6	13	507	29	Pioneer 93470	346	9-Jun

† P, Mehlich-3 extractable phosphorus; K, ammonium acetate extractable potassium; OM, Walkley-Black organic matter.

Table 5. 2. Yearly total precipitation, and average air maximum and minimal temperatures collected from an automated weather station located at each experimental research station.

Location	Precipitation†	Max Temp‡	Min Temp‡
	mm	- - - - - - - - - - °C	- - - - - - - - - -
1	502	19.2	6.0
2	819	18.0	4.7
3	482	17.8	4.7
4	558	19.7	4.4
5	1116	19.5	6.6
6	762	18.5	5.0

† Precipitation total by year.

‡ Average maximum and minimum air temperatures measured at 2 m above ground.

Table 5. 3. Significance of chelate iron (Fe) fertilizer source and placement on soybean whole plant biomass samples taken at the V-4 growth stage by location and across locations.

Parameter	Location						Across location
	1	2	3	4	5	6	
	- - - - - - - - - - - - - - - - - - - p < F - - - - - - - - - - - - - - - - - - -						
Fertilizer Placement (FP)	0.212	0.969	0.162	0.782	0.181	0.402	0.813
Fertilizer Source (FS)	0.124	0.166	0.335	0.730	0.027	0.438	0.526
FP × FS	0.199	0.211	0.550	0.077	0.325	0.498	0.388
Fertilizer Placement (FP)	- - - - - - - - - - - - - - - - - - g plant^{-1} - - - - - - - - - - - - - - - - -						
In-furrow	3.1	2.8	3.5	3.8	6.8	4.1	4.0
Surface	3.3	2.8	3.2	3.8	7.0	4.0	4.0
Fertilizer Source (FS)							
P Only	2.9	3.0	3.4	3.7	6.7b	3.9	4.0
GCH+P	3.4	2.7	3.5	3.7	6.6b	4.1	4.0
EDTA+P	3.4	2.7	3.0	3.9	7.2a	4.2	4.1
HEDTA+P	3.0	2.9	3.4	3.9	7.3a	4.1	4.1
FP × FS							
In-furrow P Only	3.2	3.0	3.6	3.8abc†	6.5	4.0	4.0
In-furrow GCH+P	3.2	2.7	3.4	3.5c	6.5	4.2	3.9
In-furrow EDTA+P	3.2	2.5	3.3	3.8abc	7.3	4.1	4.0
In-furrow HEDTA+P	2.8	3.1	3.6	4.1a	7.0	4.3	4.1
Surface P Only	2.7	3.0	3.2	3.7abc	6.8	3.9	3.9
Surface GCH+P	3.7	2.6	3.6	3.9ab	6.7	4.0	4.1
Surface EDTA+P	3.6	2.9	2.7	4.0ab	7.0	4.3	4.1
Surface HEDTA+P	3.2	2.8	3.2	3.6bc	7.6	4.0	4.1

† Different letters by category within column are significant *($p<0.10$)*.

Table 5. 4. Significance and means of chelated iron (Fe) fertilizer source and placement on phosphorus (P) concentration and uptake in whole plant samples taken at the V-4 growth stage by location and across locations.

	Location						Across	Location						Across
Parameter	1	2	3	4	5	6	location	1	2	3	4	5	6	location
	V-4 P concentration							V-4 P uptake						
	- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -							- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -						
Fertilizer Placement (FP)	0.066	0.008	0.129	0.510	0.223	0.541	0.131	0.518	0.229	0.049	0.671	0.072	0.414	0.947
Fertilizer Source (FS)	0.937	0.195	0.728	0.456	0.486	0.053	0.979	0.195	0.401	0.049	0.446	0.439	0.498	0.892
FP × FS	0.028	0.597	0.205	0.751	0.744	0.374	0.234	0.447	0.285	0.168	0.830	0.735	0.512	0.569
Fertilizer Placement (FP)	- - - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - - -							- - - - - - - - - - - - - mg plant^{-1} - - - - - - - - - - - -						
In-furrow	4.2a†	3.2a	3.2	4.1	3.2	3.6	3.6	12.9	9.2	11.3a	15.7	21.9b	15.0	14.3
Surface	4.1b	3.1b	3.2	4.0	3.4	3.6	3.6	13.4	8.7	9.8b	15.3	23.9a	14.6	14.3
Fertilizer Source (FS)														
P Only	4.2	3.1	3.2	4.0	3.5	3.7a	3.6	12.2	9.4	11.0a	14.8	23.2	14.6	14.2
GCH+P	4.2	3.2	3.2	4.2	3.3	3.6b	3.6	14.2	8.5	10.9a	15.5	21.6	14.7	14.3
EDTA+P	4.1	3.2	3.2	4.3	3.2	3.7ab	3.6	13.9	8.7	8.7b	16.4	22.7	15.3	14.4
HEDTA+P	4.2	3.2	3.2	4.0	3.3	3.6b	3.6	12.3	9.2	11.5a	15.3	24.2	14.7	14.5
FP × FS														
In-furrow P Only	4.1bc	3.2	3.2	4.0	3.3	3.7	3.6	13.0	9.8	12.6	14.9	21.2	14.6	14.2
In-furrow GCH+P	4.2ab	3.2	3.2	4.3	3.2	3.6	3.6	13.4	8.8	10.5	15.2	20.7	15.0	14.0
In-furrow EDTA+P	4.1bc	3.3	3.3	4.4	3.1	3.7	3.6	13.0	8.2	9.8	16.5	22.5	15.0	14.3
In-furrow HEDTA+P	4.4a	3.2	3.3	3.9	3.4	3.6	3.6	12.2	10.0	12.0	16.0	23.1	15.5	14.8
Surface P Only	4.2ab	3.0	3.2	4.0	3.7	3.8	3.6	11.5	8.9	9.4	14.6	25.1	14.7	14.2
Surface GCH+P	4.1bc	3.1	3.2	4.0	3.4	3.6	3.6	14.9	8.1	11.4	15.8	22.5	14.4	14.5
Surface EDTA+P	4.1bc	3.1	3.1	4.1	3.3	3.6	3.5	14.8	9.1	7.5	16.3	22.9	15.5	14.5
Surface HEDTA+P	3.9c	3.1	3.2	4.0	3.3	3.5	3.5	12.5	8.5	11.1	14.7	25.2	13.9	14.1

† Different letters by category within column are significant *($p<0.10$)*.

Table 5. 5. Significance and means of chelated iron (Fe) fertilizer source and placement on phosphorus (P) concentration at the R-3 growth stage. Trifoliate samples from the uppermost fully developed without the petiole and grain following harvest by location and across locations.

	Location						Across	Location						Across
Parameter	1	2	3	4	5	6	location	1	2	3	4	5	6	location
	Trifoliate P concentration							Grain P concentration						
	- - - - - - - - - - - - - - p < F - - - - - - - - - - - - -							- - - - - - - - - - - - - - p < F - - - - - - - - - - - - -						
Fertilizer Placement	0.129	0.198	0.004	0.018	0.468	0.092	0.105	0.814	0.107	0.001	0.8400	0.571	0.188	0.318
Fertilizer Source (FS)	0.343	0.836	0.049	0.455	0.642	0.125	0.134	0.455	0.001	0.606	0.815	0.379	0.746	0.151
FP × FS	0.124	0.796	0.345	0.835	0.088	0.643	0.025	0.468	0.247	0.696	0.577	0.285	0.926	0.396
Fertilizer Placement	- - - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - -							- - - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - -						
In-furrow	3.9	3.3	3.5a†	2.9b	3.8	4.5a	3.6	4.9	5.1	4.2a	6.3	4.8	4.6	5.0
Surface	3.7	3.3	3.2b	3.0a	3.8	4.3b	3.6	5.0	5.0	3.9b	6.3	4.9	4.4	4.9
Fertilizer Source (FS)														
P Only	4.0	3.3	3.5a	3.1	3.9	4.3	3.6	5.0	5.1	4.1	6.3	5.0	4.6	5.0
GCH+P	3.9	3.3	3.3b	3.0	3.8	4.5	3.6	5.1	5.2	4.0	6.4	5.0	4.5	5.0
EDTA+P	3.7	3.3	3.3b	3.0	3.8	4.5	3.6	5.0	4.9	4.1	6.3	4.8	4.5	4.9
HEDTA+P	3.8	3.3	3.2b	3.0	3.7	4.3	3.5	4.8	5.1	4.0	6.2	4.7	4.4	4.9
FP × FS														
In-furrow P Only	4.0	3.3	3.7	3.0	3.7b	4.2	3.6a	4.8	5.2	4.3	6.4	4.8	4.7	5.0
In-furrow GCH+P	3.8	3.3	3.4	2.9	3.8ab	4.4	3.7a	5.2	5.2	4.1	6.3	5.0	4.5	5.0
In-furrow EDTA+P	3.7	3.3	3.3	2.9	3.8ab	4.5	3.6a	4.9	4.9	4.2	6.3	4.7	4.6	4.9
In-furrow HEDTA+P	4.2	3.3	3.4	2.9	3.8b	4.2	3.7a	4.9	5.1	4.3	6.2	4.9	4.5	5.0
Surface P Only	3.9	3.3	3.3	3.2	4.1a	4.4	3.7a	5.2	5.0	3.9	6.2	5.2	4.4	5.0
Surface GCH+P	3.9	3.2	3.2	3.0	3.9ab	4.5	3.6a	5.0	5.3	3.8	6.5	5.1	4.4	5.0
Surface EDTA+P	3.7	3.3	3.3	3.0	3.8ab	4.5	3.6a	5.1	4.8	4.0	6.3	5.0	4.5	4.9
Surface HEDTA+P	3.5	3.3	3.0	3.0	3.6b	4.2	3.4b	4.7	5.0	3.8	6.3	4.4	4.4	4.8

† Different letters by category within column are significant *($p<0.10$)*.

Table 5. 6. Significance and means of chelated iron (Fe) fertilizer source and placement on Fe concentration and uptake in whole plant samples taken at the V-4 growth stage by location and across locations.

	Location						Across location	Location						Across location
Parameter	1	2	3	4	5	6		1	2	3	4	5	6	
	V-4 Fe concentration							V-4 Fe uptake						
	- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -							- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -						
Fertilizer Placement	0.332	0.274	0.462	0.549	0.714	0.971	0.354	0.977	0.332	0.254	0.598	0.699	0.784	0.368
Fertilizer Source (FS)	0.736	0.676	0.513	0.469	0.142	0.251	0.630	0.930	0.525	0.685	0.476	0.129	0.228	0.709
FP × FS	0.161	0.552	0.991	0.929	0.885	0.455	0.933	0.139	0.760	0.959	0.737	0.859	0.436	0.833
Fertilizer Placement	- - - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - -							- - - - - - - - - - - - - - mg $plant^{-1}$ - - - - - - - - - - - - -						
In-furrow	0.3	0.4	0.6	3.5	0.5	0.5	1.0	10.5	12.5	21.2	130	36.1	20.4	38.6
Surface	0.3	0.4	0.6	3.2	0.5	0.5	0.9	10.6	11.1	18.0	121	32.3	19.2	34.5
Fertilizer Source (FS)														
P Only	0.3	0.4	0.6	3.7	0.4	0.5	1.0	10.2	12.1	18.8	137	25.1	18.5	36.7
GCH+P	0.3	0.4	0.5	3.1	0.4	0.4	0.9	10.4	10.6	18.7	118	27.8	18.0	34.5
EDTA+P	0.3	0.4	0.6	2.7	0.8	0.5	0.9	11.3	11.0	18.4	105	54.9	18.5	36.8
HEDTA+P	0.3	0.5	0.6	3.7	0.4	0.6	1.0	10.2	13.4	22.4	142	29.1	24.1	40.2
FP × FS														
In-furrow P Only	0.4	0.4	0.6	4.0	0.3	0.4	1.0	12.9	11.5	21.1	144	21.0	18.2	37.8
In-furrow GCH+P	0.3	0.5	0.6	3.2	0.5	0.4	0.9	9.6	12.1	19.1	116	33.6	22.1	35.8
In-furrow EDTA+P	0.3	0.5	0.6	2.6	0.8	0.4	0.9	9.4	10.1	20.1	98.5	60.6	17.2	36.5
In-furrow HEDTA+P	0.3	0.5	0.7	4.1	0.4	0.6	1.1	10.2	12.3	24.4	163	29.1	24.1	44.3
Surface P Only	0.3	0.4	0.5	3.4	0.4	0.5	0.9	7.6	12.6	16.4	129	29.1	18.8	35.6
Surface GCH+P	0.3	0.3	0.5	3.0	0.3	0.4	0.8	11.1	9.2	18.4	120	21.9	13.8	33.2
Surface EDTA+P	0.4	0.3	0.6	2.8	0.7	0.5	0.9	13.3	10.1	16.7	112	49.1	19.9	37.1
Surface HEDTA+P	0.3	0.5	0.6	3.4	0.4	0.6	1.0	10.2	12.3	20.5	121	29.1	24.1	36.1

† Different letters by category within column are significant *($p<0.10$)*.

Table 5. 7. Significance and means of chelated iron (Fe) fertilizer source and placement on Fe concentration at the R-3 growth stage. Trifoliate samples from the uppermost fully developed without the petiole and grain following harvest by location and across

	Location						Across	Location						Across
Parameter	1	2	3	4	5	6	location	1	2	3	4	5	6	location
	Trifoliate Fe concentration							Grain Fe concentration						
	p < F							p < F						
Fertilizer Placement	0.137	0.178	0.297	0.951	0.018	0.017	0.261	0.401	0.718	0.246	0.800	0.007	0.073	0.482
Fertilizer Source (FS)	0.645	0.738	0.295	0.523	0.810	0.001	0.601	0.066	0.627	0.499	0.833	0.804	0.443	0.473
FP × FS	0.274	0.013	0.310	0.644	0.214	0.031	0.020	0.793	0.677	0.889	0.245	0.012	0.683	0.352
Fertilizer Placement	g kg^{-1}							g kg^{-1}						
In-furrow	130	144	136	207	131a†	147a	149	70.8	74.9	71.7	70.0	94.0b	67.7	75.0
Surface	122	148	139	207	123b	141b	147	68.4	74.2	69.8	72.5	100a	73.6	76.3
Fertilizer Source (FS)														
P Only	128	146	137	203	125	141b	147	64.5c	76.5	70.0	68.4	96.2	69.0	74.4
GCH+P	130	143	142	200	127	138b	147	66.8bc	72.7	69.5	65.7	98.3	73.4	74.1
EDTA+P	122	148	134	214	127	148a	148	73.8a	74.7	72.6	76.6	97.4	73.0	77.6
HEDTA+P	124	145	137	211	129	150a	150	73.3ab	74.4	71.0	74.2	95.8	67.2	76.4
FP × FS														
In-furrow P Only	129	140bcd	137	205	124	146a	146bc	66.5	75.2	70.6	60.2	87.4c	68.8	72.2
In-furrow GCH+P	140	150ab	144	203	135	145a	153a	66.1	73.2	69.8	66.2	95.1b	70.9	73.2
In-furrow EDTA+P	120	148abc	133	206	132	146a	146bc	76.8	74.8	73.4	91.0	96.8b	67.5	79.7
In-furrow HEDTA+P	130	137cd	131	215	132	152a	150ab	73.8	76.6	73.1	62.8	96.6b	63.5	74.9
Surface P Only	127	140a	137	201	126	136b	147bc	62.4	77.9	69.5	76.6	105a	69.2	76.6
Surface GCH+P	120	137d	141	197	118	131b	141c	67.5	72.1	69.1	65.3	102ab	75.8	75.1
Surface EDTA+P	125	148ab	136	223	123	150a	150ab	70.8	74.6	71.8	62.3	97.9b	78.5	75.5
Surface HEDTA+P	118	154a	143	207	126	147a	150ab	72.8	72.2	69.0	85.7	94.9b	70.9	77.9

† Different letters by category within column are significant *($p<0.10$)*.

Table 5. 8. Significance and means of chelated iron (Fe) fertilizer source and placement on manganese (Mn) concentration and uptake in whole plant samples taken at the V-4 growth stage by location and across locations.

	Location						Across	Location						Across
Parameter	1	2	3	4	5	6	location	1	2	3	4	5	6	location
	V-4 Mn concentration							V-4 Mn uptake						
	- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -							- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -						
Fertilizer Placement	0.719	0.119	0.987	0.060	0.898	0.441	0.134	0.639	0.623	0.336	0.161	0.717	0.326	0.262
Fertilizer Source (FS)	0.001	0.001	0.001	0.001	0.008	0.001	0.001	0.162	0.031	0.001	0.001	0.100	0.005	0.001
FP × FS	0.007	0.524	0.888	0.315	0.810	0.246	0.845	0.095	0.369	0.528	0.047	0.827	0.383	0.255
Fertilizer Placement	- - - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - -							- - - - - - - - - - - - - mg $plant^{-1}$ - - - - - - - - - - - -						
In-furrow	58.3	65.1	57.5	235a†	65.2	68.4	91.2	1.8	1.8	2.0	8.8	4.4	2.8	3.6
Surface	57.6	61.6	57.5	212b	64.7	66.0	86.8	1.9	1.8	1.9	8.1	4.5	2.7	3.5
Fertilizer Source (FS)														
P Only	63.4a	69.2a	67.2a	255a	71.0a	72.7a	100.0a	1.8	2.1a	2.3a	9.6a	4.7a	2.9ab	3.9a
GCH+P	59.9a	67.4a	66.1a	265a	73.1a	77.9a	101.1a	2.0	1.8b	2.3a	9.9a	4.8a	3.2a	4.0a
EDTA+P	54.2b	56.3b	43.5c	164c	59.8b	54.9c	71.9c	1.9	1.6b	1.3c	6.4c	4.2ab	2.3c	2.9c
HEDTA+P	54.3b	60.4b	53.1b	211b	55.7b	64.4b	83.1b	1.6	1.8b	1.8b	8.1b	4.0b	2.6bc	3.3b
FP × FS														
In-furrow P Only	66.1a	69.4	68.9	270	69.2	68.9	101.9	1.9a	2.1	2.5	10.1a	4.5	2.8	4.0
In-furrow GCH+P	63.8a	67.8	65.1	262	74.4	82.8	102.1	2.1a	1.9	2.2	9.3a	4.8	3.5	3.9
In-furrow EDTA+P	56.1bc	58.1	43.8	169	58.6	56.3	73.3	1.9a	1.5	1.4	6.4b	4.3	2.3	2.9
In-furrow HEDTA+P	47.3d	64.9	52.2	238	58.4	65.5	87.5	1.2b	1.9	1.9	9.6a	4.0	2.8	3.6
Surface P Only	60.7ab	69.0	65.5	240	72.9	76.5	98.0	1.6ab	2.2	2.1	9.0a	5.0	3.0	3.8
Surface GCH+P	56.1bc	67.0	67.1	267	71.8	72.9	100.1	1.9a	1.6	2.4	10.5a	4.8	2.9	4.1
Surface EDTA+P	52.3cd	54.4	43.2	159	61.0	53.4	70.4	1.9a	1.7	1.2	6.3b	4.2	2.3	2.9
Surface HEDTA+P	61.2ab	56.0	54.0	183	53.0	61.4	78.7	2.0a	1.6	1.7	6.6b	4.0	2.5	3.1

† Different letters by category within column are significant *($p<0.10$)*.

Table 5. 9. Significance and means of chelated iron (Fe) fertilizer source and placement on manganese (Mn) concentration at the R-3 growth stage. Trifoliate samples from the uppermost fully developed without the petiole and grain following harvest by location and across locations.

	Location						Across	Location						Across
Parameter	1	2	3	4	5	6	location	1	2	3	4	5	6	location
	Trifoliate Mn concentration							Grain Mn concentration						
	- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -							- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -						
Fertilizer Placement	0.009	0.173	0.810	0.241	0.153	0.349	0.052	0.503	0.323	0.189	0.178	0.082	0.017	0.278
Fertilizer Source (FS)	0.001	0.324	0.001	0.032	0.001	0.001	0.001	0.004	0.051	0.001	0.001	0.393	0.172	0.001
FP × FS	0.062	0.755	0.188	0.189	0.035	0.467	0.391	0.066	0.504	0.411	0.086	0.358	0.243	0.284
Fertilizer Placement	- - - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - -							- - - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - -						
In-furrow	65.6a†	71.2	66.7	343	57.0	70.5	112a	28.9	27.3	31.1	49.3	30.0b	35.6a	33.6
Surface	60.3b	68.2	67.1	330	55.5	68.1	108b	29.1	27.0	30.6	48.1	30.9a	34.0b	33.3
Fertilizer Source (FS)														
P Only	70.5a	71.3	74.5a	350a	60.8a	76.5a	116a	29.6a	27.5a	32.0a	50.3a	30.9	35.1	34.2a
GCH+P	67.7a	68.9	72.1a	351a	58.6a	76.1a	116a	29.4a	27.6a	32.0a	50.9a	31.0	35.0	34.2a
EDTA+P	56.0b	66.6	57.6c	314b	51.3c	59.8b	101c	28.9ab	26.5b	29.1c	46.0b	30.0	33.5	32.2c
HEDTA+P	57.8b	71.9	63.6b	330ab	54.3b	64.7b	106b	28.1b	27.1ab	30.3b	47.6b	30.0	35.5	33.2b
FP × FS														
In- P Only	74.3a	70.7	75.2	346	59.1 ab	74.9	115	29.5ab	27.7	32.6	49.0bcd	30.2	35.4	33.9
In- GCH+P	72.9ab	71.2	73.1	351	59.1 ab	77.7	117	29.5ab	27.9	31.8	52.1a	29.9	35.7	34.3
In- EDTA+P	60.8cd	68.9	58.4	329	52.8 c	63.8	105	29.4ab	26.3	29.6	47.1de	30.0	34.0	32.5
In- HEDTA+P	54.5de	73.9	60.2	346	57.1 b	65.6	109	27.1c	27.5	30.4	48.8cd	30.0	37.5	33.6
Surface P Only	66.6bc	71.8	72.8	354	62.6 a	78.2	117	29.7a	27.3	31.4	51.6ab	31.6	34.8	34.5
Surface GCH+P	62.4c	66.6	71.0	352	58.1 b	74.4	114	29.4ab	27.3	32.2	49.7bc	32.1	34.4	34.1
Surface EDTA+P	51.3e	64.3	56.7	300	49.8 c	55.9	97	28.4b	26.7	28.6	44.8e	29.9	33.1	32.0
Surface HEDTA+P	61.0cd	69.9	67.0	314	51.5 c	63.9	104	29.0ab	26.7	30.2	46.3de	30.2	33.5	32.8

† Different letters by category within column are significant *(p<0.10)*.

Table 5. 10. Significance and means of chelated iron (Fe) fertilizer source and placement on zinc (Zn) concentration and uptake in whole plant samples taken at the V-4 growth stage by location and across locations.

	Location						Across	Location						Across
Parameter	1	2	3	4	5	6	location	1	2	3	4	5	6	location
	V-4 Zn concentration							V-4 Zn uptake						
	- - - - - - - - - - - - - - - p < F - - - - - - - - - - - - - - -							- - - - - - - - - - - - - - - p < F - - - - - - - - - - - - - - -						
Fertilizer Placement	0.009	0.243	0.011	0.102	0.613	0.074	0.222	0.064	0.083	0.842	0.048	0.394	0.097	0.513
Fertilizer Source (FS)	0.001	0.001	0.415	0.002	0.434	0.624	0.004	0.325	0.006	0.410	0.001	0.001	0.962	0.031
FP × FS	0.187	0.035	0.364	0.830	0.006	0.615	0.248	0.293	0.061	0.284	0.699	0.001	0.841	0.104
Fertilizer Placement	- - - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - - -							- - - - - - - - - - - - - - mg plant^{-1} - - - - - - - - - - - - -						
In-furrow	49.6	27.4	36.3b†	39.8b	36.5	40.6a	38.3	1.5b	0.8a	1.3	1.5b	2.4	1.7a	1.5
Surface	53.3	26.5	38.9a	41.9a	35.9	37.5b	39.1	1.7a	0.7b	1.2	1.6a	2.5	1.5b	1.6
Fertilizer Source (FS)														
P Only	50.0b	24.8b	36.3	39.2b	36.3	40.7	37.5b	1.5	0.8a	1.2	1.4b	2.4b	1.6	1.5c
GCH+P	47.6b	24.5b	38.4	37.5b	35.3	39.3	37.5b	1.6	0.7b	1.4	1.4b	2.2c	1.6	1.5bc
EDTA+P	55.4a	29.3a	37.9	42.7a	35.3	38.5	40.0a	1.8	0.8a	1.1	1.7a	2.4bc	1.6	1.6a
HEDTA+P	52.9a	29.2a	38.0	44.0a	37.9	37.7	39.8a	1.6	0.9a	1.3	1.7a	2.8a	1.6	1.6ab
FP × FS														
In-furrow P Only	48.4	26.0cd	35.2	39.2	40.1ab	44.1	38.1	1.5	0.8b	1.3	1.4	2.6b	1.8	1.5
In-furrow GCH+P	43.5	23.3d	35.9	36.1	36.9abc	39.8	36.4	1.3	0.6c	1.2	1.3	2.2c	1.7	1.5
In-furrow EDTA+P	54.0	31.0a	36.4	41.0	34.5c	40.3	39.6	1.6	0.8bc	1.2	1.6	2.4bc	1.7	1.6
In-furrow HEDTA+P	52.7	29.5ab	37.9	43.0	34.6c	38.4	39.0	1.5	1.0a	1.4	1.6	2.4bc	1.6	1.6
Surface P Only	51.6	23.5d	37.5	39.2	32.4c	37.4	36.8	1.4	0.7bc	1.2	1.5	2.2c	1.5	1.4
Surface GCH+P	51.7	25.7cd	40.9	39.0	33.7c	38.8	38.6	1.9	0.7c	1.5	1.5	2.2c	1.6	1.6
Surface EDTA+P	56.7	27.7bc	39.3	44.5	36.1bc	36.7	40.4	2.0	0.8b	1.1	1.7	2.4c	1.6	1.7
Surface HEDTA+P	53.1	28.9ab	38.1	45.1	41.3a	37.0	40.6	1.7	0.7bc	1.2	1.7	3.2a	1.5	1.6

† Different letters by category within column are significant *($p<0.10$)*.

Table 5. 11. Significance and means of chelated iron (Fe) fertilizer source and placement on zinc (Zn) concentration at the R-3 growth stage. Trifoliate samples from the uppermost fully developed without the petiole and grain following harvest by location and across locations.

	Location						Across	Location						Across
Parameter	1	2	3	4	5	6	location	1	2	3	4	5	6	location
	Trifoliate Zn concentration							Grain Zn concentration						
	- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -							- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -						
Fertilizer Placement	0.050	0.736	0.207	0.880	0.067	0.211	0.091	0.832	0.120	0.039	0.218	0.015	0.958	0.418
Fertilizer Source (FS)	0.192	0.098	0.253	0.254	0.528	0.784	0.868	0.262	0.997	0.007	0.149	0.014	0.697	0.554
FP × FS	0.023	0.734	0.424	0.557	0.845	0.902	0.739	0.992	0.115	0.225	0.722	0.872	0.417	0.954
Fertilizer Placement	- - - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - -							- - - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - -						
In-furrow	48.2a†	34.2	41.1	26.2	41.6a	39.6	38.3a	44.1	36.6	34.0b	36.7	37.3a	32.8	37.0
Surface	45.9b	34.5	42.3	26.3	38.3b	38.0	37.5b	44.0	38.0	35.0a	35.4	35.9b	32.8	36.7
Fertilizer Source (FS)														
P Only	48.5	33.6b	42.5	25.3	39.0	38.1	37.6	43.6	37.4	33.8b	35.9	35.9b	32.4	36.6
GCH+P	45.7	33.5b	42.8	26.2	41.2	38.4	37.8	43.5	37.2	35.5a	37.8	38.2a	32.8	37.2
EDTA+P	45.8	35.0ab	41.0	26.6	41.3	38.8	38.0	45.2	37.4	35.1a	35.4	36.3b	32.6	36.9
HEDTA+P	48.2	35.3a	40.4	27.0	38.4	39.8	38.2	43.8	37.3	33.6b	35.1	35.8b	33.4	36.8
FP × FS														
In- P Only	50.0ab	33.1	42.7	25.9	41.8	38.7	38.4	43.7	36.8	32.9	35.9	36.9	31.9	36.7
In- GCH+P	44.7c	33.6	41.6	26.1	43.0	39.0	38.0	43.6	36.2	34.6	39.4	39.0	33.6	37.4
In- EDTA+P	45.9c	34.6	41.1	26.5	42.6	39.3	38.1	45.2	38.2	35.3	36.0	37.0	32.3	37.1
In- HEDTA+P	52.2a	35.7	38.8	26.4	39.1	41.5	38.8	44.0	35.4	33.4	35.4	36.2	33.4	36.8
Surface P Only	47.0bc	34.0	42.2	24.6	36.2	37.5	36.9	43.6	37.9	34.6	36.0	34.9	32.9	36.5
Surface GCH+P	46.7bc	33.4	43.9	26.4	39.4	37.7	37.6	43.3	38.2	36.4	36.3	37.5	32.0	37.0
Surface EDTA+P	45.7c	35.4	41.0	26.7	40.1	38.4	37.9	45.3	36.6	35.0	34.7	35.8	32.9	36.6
Surface HEDTA+P	44.3c	34.9	42.0	27.5	37.7	38.2	37.6	43.7	39.2	33.8	34.8	35.5	33.3	36.8

† Different letters by category within column are significant *($p<0.10$)*.

Table 5. 12. Significance and means of chelated iron (Fe) fertilizer source and placement on soybean seed yield.

Parameter		Location 1	2	3	4	5	6	Across location
		- - - - - - - - - - - - - - - - - p < F - - - - - - - - - - - - - - - - -						
Fertilizer Placement (FP)		0.508	0.765	0.009	0.063	0.034	0.085	0.814
Fertilizer Source (FS)		0.098	0.046	0.813	0.129	0.649	0.338	0.066
FP × FS		0.164	0.021	0.867	0.049	0.365	0.537	0.395
Fertilizer Placement (FP)		- - - - - - - - - - - - - - - - Mg ha^{-1} - - - - - - - - - - - - - - - -						
In-furrow		2.7	3.6	2.2a†	3.8b	4.5b	5.0b	3.6
Surface		2.7	3.5	2.0b	4.0a	4.7a	4.8a	3.6
Fertilizer Source (FS)								
P Only		2.8a	3.7a	2.1	3.9	4.6	5.0	3.7a
GCH+P		2.5b	3.3b	2.1	3.7	4.7	4.7	3.5b
EDTA+P		2.7ab	3.6a	2.1	4.1	4.5	4.8	3.7a
HEDTA+P		2.6ab	3.7a	2.1	4.0	4.6	4.8	3.6ab
FP × FS								
In-furrow	P Only	2.9	3.5bcd	2.2	3.7b	4.5	5.0	3.6
In-furrow	GCH+P	2.6	3.1d	2.2	3.7b	4.5	4.8	3.5
In-furrow	EDTA+P	2.8	3.6abc	2.1	4.2a	4.4	5.0	3.7
In-furrow	HEDTA+P	2.4	4.0a	2.2	3.7b	4.7	5.0	3.6
Surface	P Only	2.8	3.8ab	2.1	4.0ab	4.8	5.0	3.7
Surface	GCH+P	2.4	3.4cd	2.0	3.8b	4.8	4.7	3.6
Surface	EDTA+P	2.5	3.5bc	2.0	4.0ab	4.7	4.7	3.6
Surface	HEDTA+P	2.8	3.3cd	2.0	4.3a	4.6	4.7	3.6

† Different letters by category within column are significant *($p<0.10$)*.

Chapter 6 - Conclusion

Individual corn-soybean studies have shown various responses to tillage system and P fertilizer placements. By combining similar treatments across studies, tillage system and placement interactions have shown that corn (*Zea mays* L.) yields were highest with some type of tillage (conventional or minimum) with broadcast P applications. Soybean (*Glycine max* L.) should be planted without tillage with broadcast applications, especially when soil test P (STP) levels are below critical (20 mg P kg^{-1}). When STP are above the critical level, there was no different in P fertilizer placements in either conventional or no-tillage. Future improvements in data stewardship are clearly need to be able to compare treatments across studies. With more statistical information published with means, data could be utilized in analysis in the future.

A long-term study conducted in Kansas showed similar results as this review. In strip-tillage systems, corn yields was highest with broadcast applications. However, this management system is not the most economical. Greater net returns were achieved with deep band applications. This study has provided detailed information on long-term response of placement on corn and soybean in a two-year rotation. The value lies in ability to monitor agronomic aspects over time as well as applying economics, which is particular important for producers.

Chelated micronutrient application has been found to increase yield, however, those responses tend to vary. Glucoheptonate products have shown no adverse effects on manganese like EDTA and HEDTA and could positively affect other nutrients such as phosphorus. Higher application rates may be needed to show response, however, at this level, chelate fertilizer application may not be economical.

Appendix A - Corn response to long-term phosphorus application rate and placement under strip-tillage: additional information

Table A. 1. Planting dates and corn hybrids used at Ottawa and Scandia locations.

	Franklin County		Republic County	
Year	Planting Date	Hybrid	Planting Date	Hybrid
2006	7-Apr	Pioneer 35P17	20-Apr	Dekalb 60-19
2007	19-May	Pioneer 35P17	1-May	Dekalb 60-19
2008	14-May	Pioneer 35P17	2-May	Dekalb 60-19
2009	20-May	Pioneer 35P17	6-May	Dekalb 60-19
2010	17-Apr	Pioneer 35P17	---†	---
2011	3-May	Pioneer 35P17	---	---
2012	4-May	Pioneer 35F50RR	---	---
2013	16-May	Pioneer 636HRLLRR	---	---
2014	22-Apr	Pioneer 636AM	6-May	Pioneer 1602
2015	7-Apr	Dekalb 52-RIB	30-Apr	Pioneer 35P55
2016	---	---	---	Pioneer 1197

† Planting dates and corn hybrids used were not available.

Table A. 2. Significance of F values for the fixed effects of fertilizer treatments on corn biomass, phosphorus (P) concentration at Franklin and Republic Counties for the 10-year study and average across years.

	Year										
Parameter†	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average‡
	- - - - - - - - - - - - - - - - - - $p > F$ -										
	Franklin County										
V-6 Biomass	---§	0.695	0.030	0.001	---	0.001	0.411	0.324	0.314	0.001	0.001
V-6 P	---	0.004	0.570	0.001	---	0.001	0.001	0.001	0.001	0.008	0.001
	Republic County										
V-6 Biomass	---	0.001	0.001	---	---	0.001	0.001	0.001	0.002	0.001	0.001
V-6 P	---	0.005	0.001	---	---	0.001	0.002	0.002	0.001	0.100	0.001

† V-6 Biomass, biomass at V-6 growth stage; V-6 P, phosphorus concentration of whole plant samples taken at V-6 growth stage; V6 P uptake, calculated phosphorus uptake as a function of biomass and P concentration; Ear Leaf P, phosphorus concentration in corn ear leaf samples taken at R-2 growth stage; Grain P, phosphorus concentration in grain following harvest.

‡ 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 no collected in 2010 in Ottawa.

Table A. 3. The effects of fertilizer rate and placement on biomass of whole-plant corn samples taken at the V-6 growth stage in Franklin County.

		10 kg P ha^{-1}†	20 kg P ha^{-1}				39 kg P ha^{-1}					59 kg P ha^{-1}
Year§	Control	ST‡	BC	BC+ST	DB	DB+ST	BC	BC+ST	DB	DB+ST	BC+ST+SY	BC+ST+SY
		- g $plant^{-1}$ -										
2007	6.8	6.0	6.7	6.6	6.6	6.6	6.3	6.2	6.7	6.6	5.8	6.2
2008	12.7e¶	13.9bcde	13.5cde	15.0ab	13.2de	15.1a	13.5cde	14.5abc	14.3abcd	14.9ab	14.6abc	15.1a
2009	2.5f	3.3bc	2.5f	3.1cd	2.9de	3.1cd	2.7ef	3.3bc	3.1cd	3.6a	3.4ab	3.4ab
2011	2.4d	2.9cd	3.4bc	3.0c	2.9cd	2.9cd	3.4bc	3.7ab	3.3bc	3.7ab	3.3bc	4.0a
2012	2.9	2.9	2.8	2.8	2.8	3.1	2.7	2.9	3.1	2.4	2.4	2.7
2013	10.0	11.6	10.8	11.7	12.5	12.4	10.8	11.9	12.9	12.4	12.4	12.3
2014	3.8	4.0	4.1	4.1	4.0	4.4	4.5	4.1	5.2	4.2	3.6	4.6
2015	8.6f	11.4e	11.9e	13.3de	13.5de	14.8d	15.3cd	17.4abc	18.0ab	17.3abc	15.7bcd	18.5a

† Rate of total phosphorus (P) fertilizer (kg P ha^{-1}) applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer ST, 5 cm by 5 cm starter band; B, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast application of 20 kg ha^{-1}.

§ V-6 whole plant samples were not collected in 2006 or 2010.

¶ Different letters in rows by year indicate significant differences *($p \leq 0.1$)*.

Table A. 4. The effects of fertilizer rate and placement on phosphorus (P) concentration in whole-plant corn samples taken at the V-6 growth stage in Franklin County.

		10 kg P ha^{-1}†	20 kg P ha^{-1}				39 kg P ha^{-1}					59 kg P ha^{-1}
Year§	Control	ST‡	BC	BC+ST	DB	DB+ST	BC	BC+ST	DB	DB+ST	BC+ST+SY	BC+ST+SY
	g kg^{-1}											
2007	4.0 efg	4.3 defg	3.9 g	4.3 cdef	4.3 bcde	4.6 abc	4.0 fg	4.4 abcd	4.4 abcd	4.7 a	4.3 cdef	4.6 ab
2008	3.3	3.7	3.7	3.7	5.0	3.5	3.4	4.1	3.8	3.9	3.8	3.7
2009	3.2 h	4.3 cde	3.5 gh	4.0 ef	4.1 e	4.2 de	3.6 fg	4.8 b	4.6 bcd	5.4 a	4.5 bcd	4.6 bc
2011	3.3 g	3.9 def	3.8 ef	4.2 bc	4.1 cde	4.0 cdef	3.8 f	4.2 bc	4.5 ab	4.6 a	4.1 cd	4.4 ab
2012	3.8 g	4.7 cde	4.3 f	4.7 bcde	4.6 def	5.0 bcd	4.5 ef	4.8 bcde	5.2 abc	5.5 a	5.0 bcd	5.2 ab
2013	2.6 h	2.9 g	2.8 gh	3.2 ef	3.4 def	3.5 bcd	3.2 f	3.4 cde	3.7 ab	3.9 a	3.4 def	3.7 abc
2014	3.4 e	4.7 bc	4.2 cd	4.9 b	5.0 b	5.1 b	4.2 d	4.7 bcd	5.5 a	5.7 a	4.9 b	5.0 b
2015	2.2 e	2.4 de	2.7 cd	2.7 cd	2.9 abc	2.9 bc	2.6 cd	2.8 bc	2.9 bc	3.3 a	2.7 cd	3.1 ab

† Rate of total phosphorus (P) fertilizer (kg P ha^{-1}) applied in a three-year corn-soybean-wheat rotation.

‡ Placement of fertilizer ST, 5 cm by 5 cm starter band; B, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast application of 20 kg ha^{-1}.

§ V-6 whole plant samples were not collected in 2006 or 2010.

¶ Different letters in rows by year indicate significant differences *($p \leq 0.1$)*.

Table A. 5. The effects of fertilizer rate and placement on biomass of whole-plant corn samples taken at growth stage V-6 at Republic County.

		10 kg P ha^{-1}†	20 kg P ha^{-1}				39 kg P ha^{-1}					59 kg P ha^{-1}
Year§	Control	ST‡	BC	BC+ST	DB	DB+ST	BC	BC+ST	DB	DB+ST	BC+ST+SY	BC+ST+SY
		-g plant^{-1}										
2007	4.3e¶	7.2abc	5.7d	6.5bcd	6.2cd	7.4ab	6.8bcd	7.7ab	6.2cd	8.0a	7.1abc	6.7bcd
2008	12.5d	14.3bcd	12.7d	13.7cd	15.8ab	15.8ab	17.6a	13.7cd	12.9d	17.2a	15.2bc	15.7abc
2011	3.5d	4.5bc	4.0cd	5.0b	5.2b	6.1a	4.9b	4.9b	6.7a	6.2a	5.2b	6.8a
2012	20.1f	22.8cde	21.7ef	24.1cde	22.8cdef	27.6ab	23.8cde	21.9def	26.2abc	28.4a	23.9cde	25.2bcd
2013	10.9e	14.3cd	13.8cd	14.5cd	17.7ab	15.6bcd	13.2de	15.4bcd	17.9ab	19.0a	15.7bcd	16.2bc
2014	12.5f	15.8cde	13.9ef	14.8def	17.3abc	18.6ab	17.1abc	16.3bcd	18.0abc	19.2a	15.8cde	17.8abc
2015	8.4g	14.7abcde	12.5f	14.5bcde	13.3ef	15.0abcd	13.8def	14.0cdef	14.5bcde	16.3a	15.8ab	15.6abc

† Rate of total phosphorus (P) fertilizer (kg P ha^{-1}) applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer ST, 5 cm by 5 cm starter band; B, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast application of 20 kg ha^{-1}..

§ V-6 whole plant samples were not collected in 2006, 2009, or 2010.

¶ Different letters in rows by year indicate significant differences *($p \leq 0.1$)*.

Table A. 6. The effects of fertilizer rate and placement on phosphorus (P) concentration in whole-plant corn samples taken at the V-6 growth stage in Republic County.

		10 kg P ha^{-1}†	20 kg P ha^{-1}				39 kg P ha^{-1}					59 kg P ha^{-1}
Year§	Control	ST‡	BC	BC+ST	DB	DB+ST	BC	BC+ST	DB	DB+ST	BC+ST+SY	BC+ST+SY
	g kg^{-1}											
2007	2.9 d	3.6 c	3.5 c	4.0 abc	3.7 bc	3.8 abc	3.9 abc	3.7 bc	4.0 ab	4.2 a	3.7 abc	3.7 abc
2008	3.3 f	3.4 ef	3.7 cd	3.4 ef	3.9 bcd	3.6 de	4.1 b	3.9 bcd	3.4 ef	4.0 bc	3.9 bc	4.6 a
2010	3.2 cdef	3.2 ef	3.1 f	3.2 def	3.7 b	3.5 bcde	3.6 bc	3.4 bcdef	3.6 bcd	4.2 a	3.6 bc	4.1 a
2011	2.8 f	3.1 ef	3.4 cde	3.3 de	3.6 abc	3.5 bcd	3.5 cd	3.7 abc	3.8 ab	3.8 ab	3.5 bcd	3.9 a
2012	1.9 e	2.3 cde	2.4 cde	2.5 bcd	2.7 abc	2.3 de	3.1 a	3.1 a	2.9 ab	3.2 a	3.0 ab	3.0 ab
2013	2.9 d	3.4 bcd	3.4 bcd	3.7 abc	3.2 cd	4.1 a	3.9 ab	3.8 ab	4.2 a	4.1 a	4.0 a	4.1 a
2014	2.6 f	3.2 e	3.4 de	3.4 cde	3.2 e	3.5 cde	3.7 bc	4.0 b	3.4 de	3.7 bc	3.7 bcd	4.3 a
2015	2.9 e	3.3 de	3.8 abc	3.6 abcd	3.3 cde	3.6 abcd	3.9 a	3.8 abc	3.4 bcde	3.3 de	3.9 ab	3.4 abcd

† Rate of total phosphorus (P) fertilizer (kg P ha^{-1}) applied in a three-year corn-soybean-wheat rotation.

‡ Placement of fertilizer ST, 5 cm by 5 cm starter band; B, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast application of 20 kg ha^{-1}.

§ V-6 whole plant samples were not collected in 2006 or 2010.

¶ Different letters in rows by year indicate significant differences *($p \leq 0.1$)*.

Appendix B - Evaluating the interaction between chelated Fe fertilizer sources and placement on soybean: Additional information

Table B. 1. Significance and means of chelated iron (Fe) fertilizer source and placement on phosphorus (P) concentration and uptake in whole plant samples taken at the V-4 growth stage by location and across locations.

	Location						Across	Location						Across
Parameter	1	2	3	4	5	6	location	1	2	3	4	5	6	location
	V-4 N concentration							V-4 N uptake						
	- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -							- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -						
Fertilizer Placement (FP)	0.512	0.262	0.976	0.085	0.878	0.228	0.098	0.199	0.690	0.148	0.183	0.234	0.223	0.512
Fertilizer Source (FS)	0.447	0.803	0.861	0.071	0.423	0.389	0.061	0.209	0.463	0.437	0.241	0.018	0.597	0.418
FP × FS	0.727	0.752	0.483	0.238	0.807	0.497	0.124	0.252	0.356	0.297	0.194	0.695	0.410	0.201

† Different letters by category within column are significant *($p<0.10$)*.

Table B. 2. Significance and means of chelated iron (Fe) fertilizer source and placement on phosphorus (P) concentration and uptake in whole plant samples taken at the V-4 growth stage by location and across locations.

	Location						Across	Location						Across
Parameter	1	2	3	4	5	6	location	1	2	3	4	5	6	location
	V-4 N concentration							V-4 N uptake						
	- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -							- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -						
Fertilizer Placement (FP)	0.468	0.892	0.199	0.984	0.671	0.922	0.834	0.962	0.110	0.111	0.279	0.870	0.750	0.360
Fertilizer Source (FS)	0.745	0.307	0.039	0.757	0.283	0.584	0.108	0.421	0.397	0.959	0.639	0.791	0.970	0.723
FP × FS	0.193	0.174	0.846	0.893	0.068	0.781	0.366	0.341	0.358	0.964	0.435	0.235	0.174	0.076

† Different letters by category within column are significant *($p<0.10$)*.

Table B. 3. Significance and means of chelated iron (Fe) fertilizer source and placement on phosphorus (P) concentration and uptake in whole plant samples taken at the V-4 growth stage by location and across locations.

	Location						Across	Location						Across
Parameter	1	2	3	4	5	6	location	1	2	3	4	5	6	location
	V-4 K concentration							V-4 K uptake						
	- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -							- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -						
Fertilizer Placement (FP)	0.187	0.357	0.643	0.768	0.566	0.115	0.651	0.461	0.642	0.224	0.710	0.249	0.835	0.882
Fertilizer Source (FS)	0.749	0.328	0.554	0.291	0.650	0.083	0.443	0.083	0.732	0.344	0.227	0.303	0.760	0.707
FP × FS	0.850	0.710	0.834	0.898	0.995	0.095	0.900	0.195	0.178	0.690	0.556	0.789	0.389	0.571

† Different letters by category within column are significant *(p<0.10)*.

Table B. 4. Significance and means of chelated iron (Fe) fertilizer source and placement on phosphorus (P) concentration and uptake in whole plant samples taken at the V-4 growth stage by location and across locations.

	Location						Across	Location						Across
Parameter	1	2	3	4	5	6	location	1	2	3	4	5	6	location
	V-4 K concentration							V-4 K uptake						
	- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -							- - - - - - - - - - - - - - p < F - - - - - - - - - - - - - -						
Fertilizer Placement (FP)	0.122	0.779	0.009	0.305	0.132	0.424	0.536	0.547	0.927	0.008	0.961	0.771	0.577	0.185
Fertilizer Source (FS)	0.177	0.412	0.791	0.626	0.075	0.811	0.006	0.821	0.283	0.341	0.774	0.200	0.474	0.711
FP × FS	0.564	0.179	0.732	0.039	0.066	0.862	0.204	0.673	0.723	0.541	0.425	0.315	0.292	0.997

† Different letters by category within column are significant *($p<0.10$)*.

Appendix C - Soybean response to phosphorus fertilization and residual effects of P placement in a corn-soybean rotation under strip-tillage

Table C. 1. Cultivars and planting dates of soybean at Franklin and Republic County.

	Franklin County		Republic County	
	Date	Cultivar	Date	Cultivar
2006	22-May	Midland 432	17-May	Asgrow 3203
2007	25-May	Midland 432	4-Jun	Asgrow 3203
2008	21-May	---†	16-May	NKS 37-D5
2009	26-May	Midland 4506	---	NK-33P8
2010	27-May	---	---	---
2011	---	---	---	---
2012	29-May	Midland 4768	---	---
2013	8-Jun	Pioneer 94Y70	---	---
2014	16-May	Pioneer 4.8	21-May	---
2015	10-Jun	Pioneer P49T24SR	9-Jun	Pioneer 93470
2016	14-Apr	Pioneer 0589	9-May	Pioneer 1105

† Planting dates and cultivars used were not available.

Table C. 2. The effects of fertilizer rate and placement on corn grain and soybean seed yields at the Republic County location.

		10 Kg P ha^{-1}†	20 Kg P ha^{-1}				39 Kg P ha^{-1}					59 Kg P ha^{-1}
Year	Control	ST‡	BC	BC-ST	DB	DB-ST	BC	BC-ST	DB	DB-ST	BC-ST-SY	BC-ST-SY
							Yield, Mg ha^{-1}					
2006	3.0d	3.2bcd	3.3b	3.4ab	3.3bc	3.3bc	3.2bcd	3.6a	3.0cd	3.2bc	3.3ab	3.3ab
2007	3.5e	4.1cd	4.2cd	4.2c	4.1cd	4.1cd	4.2cd	4.4b	4.2cd	4.1d	4.4b	4.7a
2008	4.1bc	4.1bc	4.2bc	4.0c	4.3ab	4.1bc	4.3ab	4.0c	4.3ab	4.3ab	4.2bc	4.5a
2009	4.0f	4.0ef	4.3cd	4.2def	4.3cde	4.5c	4.8ab	4.4cd	3.9f	4.6bc	4.6bc	4.9a
2010	3.3c	4.2ab	4.1b	4.3ab	4.2ab	4.3ab	4.2ab	4.6ab	4.2ab	4.0b	4.7a	4.3ab
2011	3.7d	4.1c	4.2bc	4.2bc	4.3bc	4.4ab	4.7a	4.4ab	4.1bc	4.3bc	4.3bc	4.7a
2012	3.2d	3.9c	3.8c	4.0bc	4.0bc	4.0bc	4.1bc	4.2ab	4.1abc	4.1abc	4.5a	4.1abc
2013	2.6e	3.1cd	3.0d	3.2abcd	3.3abcd	3.1cd	3.4ab	3.1cd	3.3abcd	3.1bcd	3.3abc	3.5a
2014	4.9c	5.6b	5.6b	6.0ab	5.9ab	6.0ab	5.9ab	6.1ab	5.8b	6.1ab	6.4a	6.4a
2015	3.8d	4.3c	4.5bc	4.6abc	4.6abc	4.4bc	4.6abc	4.8ab	4.4c	4.6abc	4.6abc	5.0a
Average	3.5g	4.0f	4.1ef	4.2de	4.2de	4.2de	4.3bcd	4.4bc	4.1ef	4.3cd	4.5ab	4.6a

† Rate of total phosphorus (P) fertilizer (kg P ha^{-1}) applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer ST, starter band at planting; BC, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, broadcast application of 20 kg P ha^{-1} before soybean.

§ Different letters in rows by year indicate significant differences at *($p<0.10$)*.

Table C. 3. The effects of fertilizer rate and placement on corn grain and soybean seed yields at the Franklin County location.

		10 Kg P ha^{-1}†	20 Kg P ha^{-1}				39 Kg P ha^{-1}					59 Kg P ha^{-1}
Year	Control	ST‡	BC	BC-ST	DB	DB-ST	BC	BC-ST	DB	DB-ST	BC-ST-SY	BC-ST-SY
							Yield, Mg kg^{-1}					
2006	2.9	3.0	3.0	3.0	2.8	2.9	2.8	3.0	2.8	3.0	2.9	3.0
2007	1.3	1.3	1.4	1.3	1.3	1.4	1.3	1.4	1.5	0.9	1.3	1.3
2008	2.9	3.3	3.2	3.1	3.1	3.2	3.1	3.3	3.3	3.2	3.1	3.4
2009	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
2010	2.0c	2.3a	2.3a	2.2bc	2.2ab	2.2ab	2.2ab	2.3ab	2.3ab	2.3ab	2.2ab	2.3a
2011	4.4	4.5	4.8	4.9	4.7	5.2	5.0	5.1	5.2	4.7	4.8	4.9
2012	3.9e	4.2de	4.2cd	3.4bcd	4.3cd	4.7ab	4.4bcd	4.6abc	4.8a	4.6abc	4.3bcd	4.8a
2013	2.7	2.6	2.7	2.7	2.9	2.8	2.9	2.9	3.0	2.8	2.8	2.9
2014	2.2c	2.5ab	2.4bc	2.6a	2.5ab	2.7a	2.6a	2.6a	2.6a	2.7a	2.6ab	2.6a
2015	3.9b	3.9b	4.3a	4.2ab	4.2ab	4.2a	4.3a	4.4a	4.5a	4.3a	4.2ab	4.5a
Average	3.0c	3.1b	3.2ab	3.2ab	3.2b	3.3ab	3.2ab	3.3ab	3.3a	3.2b	3.1b	3.3ab

† Rate of total phosphorus (P) fertilizer (kg P ha^{-1}) applied in a two-year corn and soybean rotation.

‡ Placement of fertilizer ST, starter band at planting; BC, broadcast; DB, deep band at 15 cm deep applied with the strip-tillage; SY, soybean broadcast application of 20 kg P ha^{-1}.

§ Different letters in rows by year indicate significant differences *($p<0.10$)*.

Appendix D - Phosphorus distribution after long-term P fertilizer placement in a corn-soybean rotation under strip-tillage

Table D. 1. ANOVA for the effect of treatment on soil test phosphorus (STP) after 10-years of corn-soybean rotation under strip-tillage at Republic County.

	Position†					
Depth	IR-0	BR-3	BR-6	BR-9	BR-12	BR-15
inch	- p < F -					
0 – 7.6	0.063	0.006	0.049	0.097	0.015	0.001
7.6 – 15	0.291	0.062	0.431	0.522	0.068	0.478
15 – 22	0.342	0.042	0.258	0.223	0.109	0.423
22 – 29	0.180	0.082	0.212	0.131	0.031	0.045

† Sampled positions as related to the row: In-Row (IR) and Between-Row (BR) at 7.6, 15, 22 and 29 cm (3, 6, 9, 12, and 15 inches) from the center of the row.

Table D. 2. The effects of fertilizer placement on soil test phosphorus (STP) after 10-years of corn-soybean rotation under strip-tillage at Republic County.

	Position†					
Treatment‡	IR-0	BR-3	BR-6	BR-9	BR-12	BR-15
	- - - - - - - - - - - - - - - - - - -	-	-	mg P mg-1 -		
				0 – 7.6 cm§		
Control	6.1c¶	5.5c	6.4b	5.4b	5.5c	5.6b
BC	19.5ab	13.1b	16.6a	14.1ab	12.3ab	14.8a
BC+ST	27.7a	12.7b	17.1a	20.3a	17.2a	20.4a
DB	12.8bc	21.5a	7.4b	7.0b	7.2bc	8.3b
DB+ST	23.2ab	12.3b	8.0b	7.1b	8.3bc	8.4b
				7.6 – 15 cm		
Control	4.2	4.9b	4.7	4.3	4.1c	4.2
BC	7.6	6.9b	5.8	4.8	4.8abc	4.8
BC+ST	6.7	9.3b	5.6	5.2	5.6a	5.1
DB	53.6	58.8ab	5.3	8.7	4.3bc	4.5
DB+ST	54.1	95.3a	46.0	4.9	5.2ab	4.5
				15 – 22 cm		
Control	2.9	3.6b	3.8	3.5	3.3c	3.2
BC	4.2	4.4b	4.8	4.3	4.2ab	4.0
BC+ST	4.3	4.7b	4.8	4.7	4.4a	4.2
DB	14.9	14.4a	4.3	4.5	3.4bc	3.6
DB+ST	10.7	18.4a	11.9	4.9	4.5a	3.6
				22 – 29 cm		
Control	2.2	2.6b	2.7	2.8	2.3c	2.4c
BC	3.1	3.0b	3.4	3.7	3.2ab	3.3ab
BC+ST	3.2	3.4b	3.7	3.6	3.5a	3.2ab
DB	3.5	3.6b	2.8	2.6	2.8bc	2.7bc
DB+ST	3.8	5.1a	3.9	3.2	3.3ab	3.6a

† Sampled positions as related to the row: In-Row (IR) and Between-Row (BR) at 7.6, 15, 22, and 29 cm (3, 6, 9, 12, and 15 inches) from the center of the row.

‡ Fertilizer placement treatments: Control, no P applied; and fertilizer applied at 40 kg P ha^{-1} BC, broadcast application made before planting; ST, starter as 2 inch from the seed, dribble band at planting; DB, deep band application made 6 inches deep with the strip-tillage prior to planting.

§ Depths at 0-7.6, 7.6-15, 15-22, and 22-29 cm (0-3, 306, 6-9, and 9-12 inches) deep at each

¶ Different letters in columns by depth indicate significant differences ($p \leq 0.1$).