Enhancing soybean phosphorus management: integrating cover crop strategies and targeted fertilizer placement and timing

by

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Abstract

Phosphorus (P) management is essential for promoting soybean growth and maximizing productivity while also reducing the environmental risks associated with nutrient runoff. Cover crops (CC) are considered a promising tool in sustainable agriculture, offering benefits such as improved soil health, enhanced nutrient availability, and better soil moisture dynamics. This thesis investigates two key aspects of P management in soybean production: the influence of cover crops on P management and the effects of different P fertilizer placement techniques. The first study examined how CC impacts P management, soil moisture, and soybean productivity across multiple sites in Kansas during the 2022 and 2023 growing seasons. Using a randomized complete block design with a 3x2 factorial treatment structure, the study compared CC treatments with and without fertilizer application. Results showed that fall-planted triticale produced significantly more biomass than spring-planted oats, especially when fertilized, but increased biomass led to reduced soil moisture at the time of soybean planting. Despite variations in CC biomass and fertilizer use, no significant differences in soybean seed yield were observed across CC and fertilizer treatments. A critical biomass threshold of 2465 kg ha^{-1} was identified, beyond which soybean yield declined under Kansas environment, highlighting the need for careful management of CC growth and termination timing. Although CC improved overall P accumulation in the soil, they reduced soybean P uptake at the V4 growth stage. Phosphorus application, however, improved P concentration in soybean trifoliate leaves at later stages. The second study focused on optimizing P fertilization techniques by comparing subsurface and broadcast P applications at different rates (45, 90, and 135 kg ha^{-1}) across nine study sites in Kansas. Early season results indicated that subsurface P placement improved P uptake, particularly in soils with low Mehlich-3 soil test P values, but this advantage was

diminished by the time of R6 growth stage. No significant differences in P uptake or seed yield were found between subsurface and broadcast treatments at the end of the season. Seed yield analysis showed significant responses to P treatments at only two sites, suggesting that applied P rates frequently exceeded the requirements of the crop for optimal yield. These results emphasize the importance of aligning P application rates with soil P levels and indicate that subsurface placement could offer environmental benefits by reducing P runoff. Overall, this thesis highlights the importance of balanced P management strategies that integrate the benefits of cover crops and precise fertilizer placement to enhance soybean production and promote sustainable agricultural practices. The findings underscore the need for careful management of cover crops to balance biomass growth with moisture retention, as well as the importance of optimizing P application rates to prevent over-application and minimize environmental impacts.

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Dedication

I dedicate this thesis to my family – To my parents, Gildo and Maria, and my sister Jessica, whose constant support and encouragement have been the foundation of my success throughout this academic journey.

Chapter 1 - General Introduction and Thesis Organization

Soybean [*Glycine max (L.)*] is one of the most important crops globally due to its multi-purpose uses in food, feed, fuel, and industrial applications (Masuda and Goldsmith 2009). However, soybean growth and productivity are influenced by various factors, including the availability of phosphorus (P) in the soil (Gutiérrez-boem and Thomas 1999; Salim et al. 2023; Taliman et al. 2019). Phosphorus is essential for maximizing soybean growth and yield, playing a key role in energy transfer, photosynthesis, and other metabolic processes (Zogli, Pingault, and Libault 2017). Because soybeans are highly dependent on P, efficient P uptake is essential for achieving optimal productivity.

Despite its importance, P is often not readily available to plants as it tends to bind with soil particles, especially in soils with high levels of calcium, iron, or aluminum (Oburger, Jones, and Wenzel 2011). In addition, excessive application of P fertilizers raises environmental concerns, as P losses through surface runoff can lead to water pollution and increase the risk of eutrophication (Mardamootoo, Preez, and Barnard 2021). Therefore, improving soybean yield requires continuous advancements in agronomic practices, particularly in the efficient management of P fertilization.

In Kansas, the variability in soil types and climate poses challenges to developing specific agricultural management strategies (Sen, Zambreski, and Sharda 2023). Cover crops (CC) have gained attention as a sustainable agricultural practice that offers benefits such as improving soil health, reducing erosion, and enhancing nutrient cycling (Blanco-Canqui et al. 2011, 2015; Blanco-Canqui and Ruis 2020; Carver et al. 2022). Cover crops are defined as any crop sown before, during, or after a main cash crop and terminated before the following cash crop is planted (Hartwig and Ammon 2002). In the context of P management, CC can play an important role by cycling residual soil P and reducing the risk of P loss through runoff (Blanco-Canqui et al. 2011).

However, adopting CC must be cost-effective and not impede production gains so that farmers can consider it viable (Dagel, Osborne, and Schumacher 2014). Research indicates that CC can improve soybean productivity, particularly in humid climates. For instance, a study in Louisiana found that the benefits of CC depend on the type of CC and the biomass produced (Acharya et al. 2019). In Illinois, CC such as triticale and rye were found to reduce soybean yields in the first year of use (Acuña and Villamil 2014). Additionally, in Garden City, KS, replacing fallow with CC reduced available water for wheat planting, with higher CC biomass consuming more soil water and leading to diminished yields (Holman et al. 2018). Furthermore, CC can compete with main crops for water, which may pose a challenge in areas with limited moisture (Mitchell, Shrestha, and Irmak 2015; Rosa et al. 2021).

Despite these challenges, CC can reduce soil erosion by covering the soil surface, thus reducing the raindrop impact, slowing water runoff, enhancing water infiltration, and preventing nutrient runoff (Blanco-Canqui et al. 2011). They can also improve P availability for soybeans by recycling P from less accessible soil fractions and accumulating it on the surface through residue decomposition in low-P soils (Almeida et al. 2018; Soltangheisi et al. 2020). Integrating CC into soybean systems can improve P utilization, increase biomass production, and improve yield (Iqbal et al. 2022). Furthermore, strategically applying P fertilizers with CC can optimize P cycling, enhance soil cover, and improve P use efficiency (Caires et al. 2017). Overall, a CC has the potential to play a significant role in improving soil fertility and nutrient cycling, including P availability (Hallama et al. 2019). In addition to the role of CC in managing P, effective P management practices, including fertilizer placement, are essential for optimizing soybean productivity and minimizing environmental impact.

Phosphorus can be scarce in some ecosystems, as well as being an important cost for agricultural production and a non-renewable resource (Bagale 2021; Penuelas, Coello, and Sardans 2023; Rawat et al. 2021). Effective P management, including fertilizer placement, is crucial as it can influence plant use efficiency, nutrient availability, and soil nutrient stratification (Mallarino and Borges 2006). The placement of P fertilizer can also affect P losses; for example, when fertilizer is applied on the soil surface, it is more likely to be carried away by runoff (Kimmell et al. 2001; Smith et al. 2016). A different approach involves applying the fertilizer closer to the plant roots (subsurface) rather than broadcasting it on the soil surface, which helps reduce P losses (Withers et al. 2014).

Broadcast fertilization can effectively supply P to soybeans, but yields are often similar when smaller amounts are applied in-furrow (Rosolem and Merlin 2014). Subsurface applications concentrate P in a smaller area of soil compared to broadcasting and place it below the zone where runoff occurs, leading to less P loss compared to surface broadcasting (Kimmell et al. 2001). For instance, Smith et al. (2016) reported that subsurface P application reduced overall P runoff by nearly 97% compared to surface broadcast.

When soil P levels are high, soybeans typically show little response to additional P application (Mallarino and Borges 2005). On the other hand, when P levels are low, Cihacek, Lizotte, and Carcoana (1991) found that yield gains from fertilization were minimal, with the benefit lying more in applying P than in the method of application. Rosa, Ruiz Diaz, and Hansel (2020) observed that banded P applications were more effective during early soybean growth, while broadcast applications improved nutrient use during later stages, though yields were unaffected by the placement method.

Hansel et al. (2017) showed that band-applied P significantly increased both P uptake and concentration in soybean seeds. In soils with low P and K levels, deep banding of P and K fertilizers led to higher soybean yields than broadcasting (Hairston et al. 1990). However, broadcast applications, while easier to implement, can reduce plant height and yields, especially in soils with high P fixation (Barbosa et al. 2018).

Thesis Organization

This thesis is presented as a series of four chapters. The first chapter is an introduction that provides an overview of the topics covered in this thesis. The second chapter, "Soybean Response to Cover Crop and Fertilizer Combination: Effects on Phosphorus Uptake, Soil Moisture, and Seed Yield in Kansas", investigates the impact of cover crop biomass with and without phosphorus application on soil moisture at pre-plant and post-harvest, cover crop phosphorus uptake, phosphorus use efficiency indicators in soybean, and soybean seed yield across nine sites during two growing seasons in Kansas. The third chapter, "Evaluation of Soybean Response to Phosphorus Fertilizer Placement and Rates", evaluates the response of phosphorus fertilizer in different placements (broadcast and subsurface) on soybean phosphorus use efficiency indicators and seed yield. The final chapter (chapter four) provides a general conclusion and summary of the results conducted in this thesis.

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Chapter 2 - Soybean Response to Cover Crop and Fertilizer Combination: Effects on Phosphorus Uptake, Soil Moisture, and Seed Yield in Kansas

Abstract

Phosphorus (P) plays a critical role in supporting plant growth and maximizing crop yields, but its availability is often limited in agricultural soils. Cover crops (CC), widely used to improve soil health, can also influence nutrient availability and moisture dynamics in the soil. This study aimed to evaluate the impact of cover crops on phosphorus management, soil water content, and soybean [*Glycine max (L.)*] productivity across multiple sites in Kansas. Field experiments were conducted in 2022 and 2023, using a randomized complete block design with a 3x2 factorial treatment structure including CC treatments with and without fertilizer application. The findings revealed that fall-planted triticale produced significantly more biomass than spring-planted oats, particularly with fertilization. However, increased CC biomass was associated with reduced soil moisture at the time of soybean planting. Despite the variations in CC biomass, soil moisture at planting, and fertilizer application, no significant differences in soybean seed yield were observed across the various treatments. Further analysis identified a critical biomass threshold of 2465 kg ha^{-1}, beyond which soybean yield declined, underscoring the need to carefully manage CC growth and termination timing. In terms of P uptake, the presence of CC enhanced overall P accumulation but reduced soybean P uptake at the V4 growth stage. Although P application improved P concentration in soybean trifoliate and total P uptake, interactions between CC and fertilizer application did not significantly affect seed P uptake. The study highlights the need for balanced P management strategies to optimize soybean production while considering the role of cover crops in nutrient cycling.

Introduction

Soybean is a widely cultivated legume that plays a crucial role in global food security and agricultural sustainability, substantially impacting both food supply and diet quality (Hartman et al. 2011; Masuda and Goldsmith 2009). However, soybean growth and productivity can be significantly affected by several factors, including the availability of phosphorus (P) in the soil and cover crop (CC) management (Gutiérrez-boem and Thomas 1999; Taliman et al. 2019).

Nutrient management is a critical challenge facing modern agriculture, and maintaining adequate levels of macro and micronutrients, such as P, is crucial for optimal soybean growth and yield (Bagale 2021). Phosphorus is a vital nutrient for plants, needed for important processes like cell division, energy production, building molecules, maintaining membranes, and photosynthesis (Rawat et al. 2021). Studies have shown that P application can significantly enhance the water use efficiency and development of soybean plants during the reproductive stage, consequently increasing seed yield (Feng et al. 2021; He et al. 2019; Jin et al. 2005). Phosphorus deficiency is common in many agricultural regions, necessitating P fertilizer application to increase plant uptake and ensure soybean productivity (Heuer et al. 2017).

Phosphorus management poses challenges in agriculture, including P depletion or accumulation in the soil, and environmental concerns related to P runoff that causes algae blooms that deteriorate water quality (Haque 2021). Moreover, P is a finite resource, increasing the importance of using it efficiently and recycling it in agricultural production (Scholz et al. 2013). Addressing these challenges is crucial to sustain soil fertility and ensure long-term agricultural production (Baker et al. 2015; Auteri, Saiano, and Scalenghe 2022).

The implementation of various agricultural best management practices has been suggested to minimize nutrient losses from the field (Prokopy et al. 2008), and the integration of

CC and strategic fertilizer applications has gained attention in recent years for addressing low P availability and enhancing soybean performance. Cover crops have been encouraged to be used ahead of crops such as corn and soybeans, seeking the principles of a more conservationist agriculture. Hartwig and Ammon (2002) defined CC as any crop sown before, during, or after a primary cash crop and terminated before planting the following cash crop. In the Midwest region, more farmers are embracing planting CC alongside their main crops like soybeans. This shift is driven by the recognized benefits of CC in improving soil quality, as they can potentially reduce the environmental impacts of P fertilizer, decrease erosion losses, and increase water infiltration in the soil (Blanco-Canqui et al. 2011, 2015; Blanco-Canqui and Ruis 2020; Carver et al. 2022). By reducing the reliance on external inputs, CC potentially offers a natural solution to enhancing soil fertility and reducing soil erosion and nutrient runoff (Blanco-Canqui et al. 2011; Withers et al. 2014). This can help farmers reduce costs by promoting nutrient cycling, minimizing chemical use, and reduce nutrient losses through runoff (Rivière, Béthinger, and Bergez 2022).

Cover crops can play an important role in improving soil fertility and nutrient cycling, including the availability of P (Hallama et al. 2019). Cover crops can enhance P availability in soybeans, primarily by recycling P from less labile fractions and accumulating it on the surface after the decomposition of residues in low-P soils (Almeida et al. 2018; Soltangheisi et al. 2020). By integrating CC into soybean systems, farmers have the potential to enhance P utilization, thereby increasing biomass production and crop yields (Iqbal et al. 2022). Furthermore, the strategic application of P fertilizers with CC can further optimize P cycling, soil cover, and ensure better timing and operational efficiency during soybean planting (Caires et al. 2017).

In temperate regions, the strategic use of CC after harvesting cash crops, such as corn and soybeans, can extend the period of soil cover, reducing the risk of erosion and nutrient leaching (Daryanto et al. 2018). In semi-arid regions, the use of CC can be more challenging due to increased water competition potential between CC and the primary crop (Mitchell, Shrestha, and Irmak 2015). However, the optimization of planting and termination timing can mitigate this impact of CC on soil moisture (Rosa et al. 2021).

In drier regions of Kansas, a common practice to reduce water consumption is the crop-fallow system, in which the farmers grow one crop and leave the field fallow during the rest of the year (Yeo et al. 2014). Cover crops reduce fallow periods in cropping systems, thereby increasing field diversity and reducing soil exposure. Keeping the soil exposed in the period without growing crops can cause soil disaggregation by the impact of rain and, consequently, runoff of soil and nutrients by water or even losses by the wind (Havlin et al. 2005; Huo et al. 2021). Cover crops can decrease sediment losses as they cover the soil surface when no crops are growing in the field, reducing the energy of raindrops and the speed of water runoff, increasing water infiltration into the soil, and avoiding nutrient losses (Blanco-Canqui et al. 2011).

Similar to other cultural methods that involve costs with additional management implementations, the adoption of CC must avoid causing production setbacks to be considered feasible by farmers (Dagel, Osborne, and Schumacher 2014). In a study in Louisiana, Acharya et al. (2019) found that CC are beneficial for soybean productivity in humid climates and that the effects vary according to the type of CC and the biomass produced. However, a study conducted in Illinois showed that using CC, such as triticale and rye, reduced soybean yields in the first year of the experiment (Acuña and Villamil 2014). In a study conducted in the Semiarid Central Great Plains region, specifically in Garden City, KS, researchers found that substituting fallow with a CC reduces the available water at wheat planting, with CC that generated higher biomass consuming more soil water and consequently leading to diminished yields (Holman et al. 2018). The same researchers demonstrated that in humid years, rainfall throughout the growing season sufficiently mitigated yield losses, whereas in dry years, the use of CC led to productivity reductions of up to 70% (Holman et al. 2018).

Cover crops are not widely used in Kansas, and their effects, particularly in combination with P fertilization, have not been extensively studied. This study aims to address this gap by assessing the impact of planting CC before soybeans on soil moisture, seed yield, and P uptake, as well as exploring the interactions between CC and fertilizer application across various locations in Kansas. We hypothesized that CC with high biomass could reduce soil moisture, potentially decreasing productivity, while CC with lower biomass may improve seed yield by maintaining water availability and gradually releasing nutrients. Additionally, CC could enhance P uptake by recycling P to the soil surface after decomposition, offering a window of opportunity for better fertilizer placement and timing.

Material and Methods

Nine soybean sites were established in 2022 and 2023 across Kansas. A description of each location is presented in Table 2.1. For all sites, row spacing was 76 cm, and plot size was 12.2 m in length and 3 m in width (36.6 m^2). The experimental design was a randomized complete block design with four replications and the treatment structure was a 3x2 factorial. The treatments comprised a control, which did not involve a CC or application of fertilizer, along with treatments involving the application of fertilizer at a rate of 45 kg ha^{-1} of P_2O_5. These applications were done in combination with the CC planting, including triticale and oats, during late fall and early spring, respectively. Additionally, in early spring, at the same time as the spring CC was planted, the same rate of fertilizer (45 kg ha^{-1} of P_2O_5) was applied without CC. The fertilizer source was MAP (11-52-0).

In 2022, there was only one CC (oats), which was planted in the spring. In 2023, triticale was added to verify the effect of a winter CC with potentially higher biomass . The cover crops were scheduled for chemical termination either the day before or the day after soybean planting, except at Site 4, where termination occurred 12 days prior to planting to accommodate farm field operations

A composite soil sample of 15 cores was collected from each replicate (block) at the 0-15 cm depth for soil characterization before the establishment of the study. The soil samples were air-dried at 40 ^{o}C and sieved through a 2 mm mesh. Subsequently, the processed samples were stored in plastic cups for analysis. Extractable P was quantified utilizing the Mehlich-3 method, as described by Frank, Beegle, and Denning (1998). The resulting extracts were analyzed by colorimetric analysis. Soil organic matter (SOM) content was determined by loss in ignition (Combs and Nathan 1998). Soil pH levels were measured using a 1:1 ratio of soil to water, following the procedure detailed by Watson and Brown (1998).

To calculate the total biomass and P uptake of the CC, a composite sample was collected from three distinct areas within each plot. Each subsample encompassed an area of 0.3266 m^2, totaling 0.9798 m^2 per plot. Cover crop plants were uniformly cut close to the soil from this area and subsequently dried in a forced air oven at 60°C for one week. Once dry and weighed, plants were ground to pass through a 2 mm sieve and then analyzed for total P content using the sulfuric peroxide digest as described by (Lindner and Harley 1942). The total P was determined using inductively coupled plasma (ICP) spectrometer (720-ES ICP; Varian Australia Pty Ltd, Mulgrave, Victoria, Australia). Phosphorus concentration and biomass were used to calculate total plant P uptake.

Soybean tissue samples were taken during the vegetative and reproductive growth stages. Whole plant samples were taken in the V4 (four trifoliate fully developed) and R6 (seed contains a green seed that fills the cavity in one of the four uppermost nodes on the main stem) growth stages. Trifoliate samples were taken in the R3 growth stage (pods are 4.76 mm long on one of the four uppermost nodes on the main stem with fully developed leaf). The V4 growth stage sampling was accomplished by removing fifteen soybean plants at random from non-harvest rows of each plot. For the R3 growth stage, sampling was done collecting thirty trifoliate leaves from the top of the plants at random from harvest rows of each plot. For the R6 growth stage, the sampling was accomplished by removing six soybean plants at random from the harvest rows of each plot. Soybean plant samples were dried in a forced air oven at 60 ^{o}C for a minimum of six days and the whole plant samples (V4 and R6) were weighted for biomass calculation. After drying and weighing, the plants were ground to pass through a 2 mm sieve. The total P content was analyzed using a sulfuric peroxide digest, and subsequently determined with an inductively coupled plasma (ICP) spectrometer. The product of P concentration and biomass was used to quantify total P uptake at the V4 and R6 growth stages.

A Wintersteiger combine (Wintersteiger Inc. – headquartered in Salt Lake City, Utah, USA), fitted with a 1.4-meter head was used to quantify soybean seed yield. The two central rows of each plot were harvested, totaling an area of 18.58 m^2. Seed weight was recorded, and subsamples were taken from each plot and analyzed for moisture using a Dickey-John GAC-2500-AGRI seed analysis computer (DICKEY-john Corp – headquartered in Auburn, Illinois, USA). Seed yield was calculated by adjusting the moisture to 13%. The seeds were ground and analyzed for P content using the same methodology as the tissue samples.

Soil moisture was measured post-harvest in 2022 and 2023 and at planting only in 2023, all at a depth of 0-12 cm using a HydroSense II Handheld Soil Moisture Sensor (Campbell Scientific's – headquartered in Logan, Utah, USA).

The effect of CC on soybean yield was quantified and standardized by calculating the relative yield (RY %) as the seed yield from the treatment with CC divided by the seed yield from the treatment without the CC and multiplied by 100 to obtain a percent value (Eq. 1). This calculation was conducted separately for treatments without fertilizer application and treatments with fertilizer application. Resulting RY % values from the four replicates were used in the regression analysis to evaluate the effect of CC biomass on soybean seed yield.

Eq. 1:

$$RY\ \% = \frac{Seed\ \ Yield\ with\ CC}{Seed\ \ Yield\ without\ CC}\ x\ 100$$

Where RY %, relative yield of plots with cover crops compared to those without; Seed Yield with CC, mean yield from plots with cover crops; Seed Yield without CC, mean yield from plots without cover crops.

To calculate the relative moisture (RM %), the soil moisture content from the treatment with the CC was divided by the soil moisture content from the treatment without the CC and multiplied by 100 to obtain a percent value (Eq. 2). This calculation was also performed separately for treatments without fertilizer and treatments with fertilizer application.

Eq. 2:

$$RM\ \% = \frac{Moisture\ Content\ with\ CC}{Moisture\ Content\ without\ CC}\ x\ 100$$

Where RM %, relative moisture content of plots with cover crops compared to those without; Moisture Content with CC, moisture content from plots with cover crops; Moisture Content without CC, moisture content from plots without cover crops.

Data were analyzed by site and combined using the lme4 package in R 4.3.0, using RStudio (Version 2023.06.1+524), assuming block as a random factor in the Analysis of Variance. When combined, sites were also considered as random effect in the model. The t-tests use Kenward-Roger's method, and the statistical significance was set at alpha < 0.05. For regression analysis, the geom_smooth function was used from ggplot2, with method "lm". The plateau linear model was fit using the nonlinear least square 'nls', with the package nlraa. Figures were made using ggplot2 package also using RStudio (RStudio Team 2021).

Results and Discussion

Climate and Soil Data

The monthly normal accumulated precipitation from 1981 to 2010 and monthly observed accumulated precipitation for each site year are shown in Figure 2.1. For all the experimental sites in 2022 and 2023, there was less accumulated precipitation than normal. Sites 2, 5, 6, 7, and 9 were irrigated and therefore depended less on precipitation than sites 1, 3, 4, and 8.

The variability in precipitation across the experimental sites highlights a significant challenge for farmers when implementing CC in areas without irrigation. According to Kasper et al. (2022), CC can lead to deficits in soil moisture and crop failure in areas of low precipitation and without access to irrigation.

The study sites provided a wide range of soil conditions (Table 2.2). Soil pH values ranged from 5.3 to 7.1, with site 3 having the lowest pH and site 4 having the highest. In terms of SOM, values ranged from 16 g kg^{-1} to 37 g kg^{-1}, with site 7 at the low end and site 2 at the high end of this range. Soil test phosphorus using Mehlich-3 (STP-M3) levels for most sites were between 2.8 mg kg^{-1} at site 2 and 17.8 mg kg^{-1} at site 9. An exception was site 3, which had a notably high STP-M3 of 78.8 mg kg^{-1}. Clay content in the soil was highest at Site 6 (34%) and lowest at Site 7 (11%), and sand content was highest at Site 9 (52%) and lowest at Site 8 (8%).

A study made in central, northern and northeast Iowa identified the critical soil test P using Bray-1 (STP-B1) for soybean across sites and years to be between 12 to 18 mg kg^{-1} (Dodd and Mallarino 2005). Sucunza et al. (2018) found results for critical STP-B1 values that suggest the critical value for soybean to be around 14.3 mg P kg^{-1}. In a study conducted in Kansas, Roa-Acosta and Ruiz Diaz (2022), found a strong correlation between STP-M3 and STP-B1 (R^2 = 0.93), with the conversion from STP-B1 to STP-M3 represented by the equation: $y = -1.22 + 1.08x$, where y is STP-M3 (mg kg^{-1}) and x is STP-B1 (mg kg^{-1}).

Cover Crop Biomass

In 2022, the application of P fertilizer alongside CC planting led to a significant increase in oat biomass, averaging an increase of 515 kg ha^{-1} across the three sites (Table 2.3). Subsequently, in 2023, the introduction of triticale to the study revealed a biomass of 1221 kg ha^{-1} higher than oats across sites with fertilizer application, and 661 kg ha^{-1} without fertilizer application (Table 2.3). Related studies found that late-terminated CCs, having more time to grow, significantly outperformed the early-terminated ones in biomass production (Alfonso et al. 2020; Ruis et al. 2018). Considering the difference in growth periods between species, the higher biomass observed for triticale can be attributed to its longer growing period. Planted in the fall, the triticale had more time to develop and accumulate biomass than oats planted in the spring.

Considering the effect of fertilizer application, the addition of 45 kg ha^{-1} exhibited a biomass of 698 kg ha^{-1} greater than those without fertilizer in 2023 (Table 2.3). This observation aligns with findings from another study, which demonstrated that phosphorus fertilization positively impacts biomass production in various cover crops, and significantly increases the concentration of phosphorus, nitrogen, and potassium in the cover crops (Araújo et al. 2021; Bourns et al. 2024).

Soil Moisture

Soil moisture at the planting of the soybean crop in 2023 was significantly affected by CC across sites, with treatments without CC having a soil moisture content of 0.23 cm^3 cm^{-3}, while treatments with oats had a soil moisture content of 0.16 cm^3 cm^{-3} and triticale had 0.18 cm^3 cm^{-3} (Table 2.4). As the CC grows, it uses nutrients and water from the soil, which may be needed for the cash crop later in the season. The relationship between CC biomass and relative soil moisture at planting in our study reveals a significant decrease in soil moisture with increasing cover crop biomass (Figure 2.2a). Relative soil moisture compares the moisture levels of plots with and without CC, with values below 100% indicating lower moisture in plots with CC. The biomass produced by the CC is correlated to the amount of water and nitrogen that it uptakes from the soil (Sinclair and Rufty 2012), explaining the lower soil moisture at the time of planting when CC were used in comparison to the treatments without CC.

Supporting these findings, another study indicated that CC reduced soil water content by an average of 18% at planting in dryland systems, potentially impacting yields when annual precipitation is below 700 mm (Deines et al. 2023). A study conducted during the 2012 drought in Iowa found that rye CC in a corn-soybean rotation did not significantly lower soil moisture and, at certain depths, soil moisture was slightly higher after terminating the CC, suggesting no negative impact on soil moisture. However, this was still under conditions where precipitation exceeded 800 mm (Daigh et al. 2014). In Kansas, the precipitation sometimes is lower than 600 mm in some regions like the western part of the state (Rahmani et al. 2015), and those levels can likely exacerbate the reduction in soil moisture at planting of the cash crop caused by the CC.

Soil moisture from the 0-12 cm depth after the soybean harvest did not show significant differences between treatments with or without CC for the years 2022 and 2023 (Table 2.5). Likewise, our findings show no significant reduction in relative soil moisture after harvest with increasing CC biomass (Figure 2.2b). This was probably because rainfall during the season was sufficient to balance soil moisture during the development of soybeans, reaching similar levels as the control during the growing season. Similarly, a study conducted in Nebraska found that winter CC had minimal and infrequent effects on soil moisture under sufficient precipitation conditions (Barker et al. 2018).

Cover Crop Phosphorus Uptake

The application of fertilizer alongside CC planting led to an increase in P uptake in the CC in 2022, averaging an increase of 1.4 kg ha^{-1} across the three sites (Table 2.6). In 2023, the introduction of triticale revealed a P uptake of 1.34 kg ha^{-1} greater compared to oats across the six sites. Additionally, in 2023, the fertilizer application exhibited P uptake of 2.21 kg ha^{-1} greater than the treatment without fertilizer (Table 2.6). Although fertilizer application increased P uptake and triticale outperformed oat treatments, there was no interaction between the effects of Fertilizer and CC in 2023 (Table 2.6).

The increase in P uptake by the CC when fertilizer was applied alongside CC planting suggests that the targeted fertilization in the CC is effective in promoting nutrient uptake by the CC. In 2023, the P uptake by the triticale was higher than oats. Additionally, considering the growth periods between the species, triticale had already emerged when temperatures started rising in the following spring, giving more time to develop compared to oats, which were being planted at that time. The extended growth period for triticale likely contributed to its greater biomass and P uptake. The biomass data across locations from 2023 supports this, showing that oats had a biomass of 1400 kg ha^{-1} without fertilizer and 1819 kg ha^{-1} with fertilizer, while triticale had a biomass of 2061 kg ha^{-1} without fertilizer and 3039 kg ha^{-1} with fertilizer (Table 2.3). This trend suggests that the longer growth period allowed the CC to produce more biomass (Alfonso et al. 2020; Poudel et al. 2023), which in turn led to greater P uptake.

Soybean Phosphorus Uptake at the V4 Growth Stage

In 2022, the use of oats ahead of soybeans significantly reduced P uptake by the soybean by 0.24 kg ha^{-1} when considering the effect of CC, and the application of fertilizer led to an increase in P uptake of 0.09 kg ha^{-1} when compared to the treatments without fertilizer (Table 2.7). This reduction in P uptake can be attributed to differences in biomass production at the V4 stage of soybean. The soybean biomass for the treatment without CC or fertilizer was 17.4 kg ha^{-1}, while the treatment without CC but with fertilizer application had a slightly higher biomass of 20.0 kg ha^{-1}. In comparison, the treatment with oats and no fertilizer application resulted in a lower biomass of 12.1 kg ha^{-1}, and the addition of fertilizer to the oats treatment increased the biomass to 13.0 kg ha^{-1}.

In 2023, there was a significant difference in P uptake when fertilizer was applied, increasing the P uptake by 0.34 kg ha^{-1} (Table 2.7). When considering the effect of CC, the addition of oats or triticale before soybean resulted in a reduction in soybean P uptake, with the treatment without CC showing the highest uptake with 2.26 kg ha^{-1} (Table 2.7). The biomass data further supports this trend. For treatments without CC or fertilizer, the soybean biomass was 37.3 kg ha^{-1}, increasing to 44.8 kg ha^{-1} with the addition of fertilizer. In contrast, the treatment with oats and no fertilizer produced a biomass of 33.1 kg ha^{-1}, with a slight increase to 33.6 kg ha^{-1} when fertilizer was applied. The triticale treatment without fertilizer had a biomass of 31.2 kg ha^{-1}, which decreased slightly to 30.9 kg ha^{-1} with fertilization.

The trend observed on these results is that, while fertilization can enhance biomass production and P uptake in the absence of CC, the introduction of oats or triticale may limit the growth of soybeans in the early season even when fertilizer is applied to the CC. The nutrient release pattern varies with the type of residue and the microbial communities present in the soil, with non-legumes residues decomposing more slowly compared to legume residues, resulting in a slow nutrient release into the soil (da Silva et al. 2022). This outcome suggests that the CC may compete with the subsequent soybean crop for nutrients and/or water in the early season, as the CC is not decomposed yet to release nutrients back to the soil and reduced the water content of the soil at planting when higher CC biomass was observed (Figure 2.2a). Additionally, as reported by Yang et al., (2021), the CC residue on the soil surface can reduce soil temperature in the spring, potentially slowing seed germination, seedling emergence, and early crop growth. This cooling effect could be a contributing factor to the lower biomass and P uptake observed in the early season in our study.

Soybean Phosphorus Concentration at the R3 growth Stage

The analysis of P concentration at the R3 growth stage across locations in 2022 showed no difference among treatments with and without CC or interaction with fertilizer application, but the application of fertilizer significantly increased the P concentration in the trifoliate at R3 by 0.3 g kg^{-1} (Table 2.8). Similarly, in 2023, treatments with fertilizer showed a greater P concentration in the trifoliate, reflecting an increase of 0.3 g kg^{-1}, as observed in 2022 (Table 2.8).

In 2022, only site 2 showed a significant response to fertilizer application at $p \leq 0.05$, while the other analyses showed no significant response to fertilizer, CC, or the interaction between fertilizer and CC. In 2023, four out of six sites showed a significant response to fertilizer application, and two sites had a significant response to CC (Sites 4 and 5). None of the nine sites showed a significant main effect of the interaction between fertilizer application and CC (Table 2.8). This indicates that while fertilizer application had a clear impact on P concentration in the soybean trifoliate at the R3 growth stage, CC and their interaction with fertilizer rates did not significantly influence the outcomes.

Soybean Phosphorus Uptake at the R6 Growth Stage

For the P uptake at the R6 growth stage, the results across sites from 2022 mirrored those observed for the P concentration in the trifoliate at the R3 growth stage, with no significant differences among the treatments with CC, and with a significant increase of 4.7 kg ha^{-1} in P uptake when fertilizer was applied, but without interaction between the effects of fertilizer and CC (Table 2.9). In the year 2023, the same pattern was observed, where the CC treatments did not have any significant effect or interaction with fertilizer application, but the addition of fertilizer resulted in an increase in P uptake of 3.3 kg ha^{-1} at the R6 growth stage (Table 2.9). Tian et al. (2020) also found that P fertilization increased the P uptake and biomass of the soybean plants. However, there was no significant response to CC or the main effects of the interaction between CC and fertilizer application, following the same trend observed on the P concentration at the R3 growth stage. This suggests that, while the fertilizer application had a clear impact on the results, the use of CC and their interaction with P rates did not significantly influence the outcomes of the soybean crop later in the growing season.

A study that evaluated the P release over time after the incubation of the residue of different species demonstrated an initial increase in P release within the first 10 days, and this release remained nearly constant up to the 120-day mark evaluated in the study (Vanzolini et al. 2017). Those results, combined with the P uptake of the CC observed in this study, may indicate that soybean plants experienced lower P levels at the beginning of their development in soils with low P, followed by a gradual release of P throughout the growth period, replenishing P levels by the end of soybean development.

Soybean Phosphorus Uptake in the Seeds

Based on the P uptake findings in the seeds, consistent results were observed across both the 2022 and 2023 study years, showing no significant effects of CC treatments and interactions between fertilizer and CC effects. However, there was a slight increase of 1.5 kg ha^{-1} in P uptake by the seeds when fertilizer was applied (Table 2.10). Specifically, looking at the level of significance of the individual sites, sites 5 and 6 showed significant response to fertilization, while none of the other sites from 2022 or 2023 had a significant response. These results from 2023 suggest that, while P fertilization can influence P uptake in the seeds in some locations

(Fageria, Moreira, and Castro 2011), the use of CC and their interaction with fertilizer application do not have a significant impact on the final P uptake in soybean seeds. In 2022, responses were generally similar, except that the sites 2 and 3 showed significant response to CC (Table 2.10).

Seed yield

Our investigation revealed no significant differences in soybean yield when CC were integrated into the system or when fertilizer was applied to the CC (Table 2.11). These results indicate that neither the presence of CC nor fertilizer application significantly impacted soybean seed yield during these periods. A similar study found that using CC can decrease corn and soybean yield compared to fields without CC, and that these reductions varied depending on factors such as soil quality, temperature during the growing season, and rainfall patterns (Deines et al. 2023). When examining post-harvest moisture levels (Table 2.5), we also observed no significant differences between treatments with or without cover crops. This suggests why soybean yields did not vary significantly across locations when comparing treatments with and without CC. A study made by Nielsen et al. (2016) demonstrated inconsistent results regarding CC effects on wheat yield. On their study, half of the datasets showed a decrease in wheat seed yield with CC use, with this trend not being consistent across all cases. It suggests that factors beyond water usage could influence yield in the presence of the CC.

Looking at the yield results for the individual sites (Table 2.11), we can observe the yield response for each CC versus fertilizer treatments, indicating variability within each treatment across the sites. The same observation was made for the CC biomass (Table 2.3). This relationship was explored deeper using plateau-linear modeling between CC biomass and relative yield of the soybean crop, where it was possible to evaluate each treatment from each site independently (Figure 2.3). From this analysis, a noteworthy trend was observed, where the results demonstrated that the addition of CC did not negatively affect the seed yield until the biomass exceeded the threshold of 2465 kg ha^{-1}. Beyond this point, a substantial decline in soybean yield became evident in comparison to treatments without CC. This finding underscores the critical threshold at which CC biomass may begin to exert detrimental effects on soybean seed yield, highlighting the importance of carefully managing CC growth, particularly through CC termination timing, to maximize soybean productivity. A study in Louisiana showed that CC does not reduce productivity or soil moisture even with biomass greater than 4,000 kg ha^{-1} (Acharya et al. 2019). This is probably because the average precipitation in the state was higher than in Kansas, so CC evapotranspiration did not affect soybean productivity. However, in Kansas, where precipitation is limited, terminating the CC earlier, with lower biomass, may be a strategy to optimize the benefits of using CCs and also reduce the likelihood of significant soybean yield penalties (Marcillo and Miguez 2017; Qin et al. 2021).

Conclusions

Cover crops resulted in varying biomass production across experimental years and individual sites, with triticale producing higher biomass due to its longer growth period. Fertilizer application further enhanced CC biomass, highlighting the importance of nutrient availability. However, increased CC biomass reduced soil moisture at soybean planting, revealing a trade-off between the benefits of CC and soil moisture depletion, especially in regions with limited precipitation like Kansas. Post-soybean harvest soil moisture levels did not differ significantly across treatments.

In terms of P uptake, the application of fertilizer combined with CC significantly increased P uptake in the CC, with triticale outperforming oats due to its longer growth period. However, the presence of CC reduced the biomass and P uptake of soybean plants at the V4 growth stage, likely due to competition for P and water during the early stages of growth, and reduced soil temperatures slowing soybean growth. At the R3 stage, P fertilization significantly enhanced P concentration in soybean trifoliate, while the CC and interaction between CC and fertilization did not show significant effects. Similar trends were observed at the R6 stage, with P fertilization increasing overall P uptake, though CC and the interaction with fertilizer did not have a significant impact. Additionally, neither CC nor P application significantly influenced seed P uptake in 2022, and fertilization slightly increased the P uptake by the seeds in 2023.

Finally, although soybean seed yield did not vary significantly with different CC and fertilizer treatments across sites, a critical biomass threshold of 2465 kg ha^{-1} was identified, beyond which a decline in yield occurred. This highlights the importance of managing CC growth and termination timing to optimize soybean productivity, particularly in regions with limited precipitation. These findings emphasize the role of P fertilization in improving soybean P availability and underscore the need for adaptive management practices to balance potential CC benefits and moisture availability. Future research should focus on the interactions between climate, soil, and crop management practices to increase cover crop adoption.

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Tables and Figures

Table 2.1. Study location, soil classification, previous crop, and planting date information.

Site	Year	County	Soil Classification		Previous Crop	Planting Date			Irrigation
			Series	Subgroup		Triticale	Oat	Soybean	mm
1	2022	Riley	Reading	Pachic Argiudolls	Soybean	-[a]	Mar 29	May 22	-[b]
2	2022	Republic	Crete	Pachic Udertic Argiustolls	Corn	-	Mar 17	Jun 13	190
3	2022	Republic	Crete	Pachic Udertic Argiustolls	Corn	-	Mar 17	May 20	-
4	2023	Riley	Kennebec	Cumulic Hapludolls	Soybean	Nov 11	Mar 13	May 24	-
5	2023	Republic	Crete	Pachic Udertic Argiustolls	Corn	Nov 22	Mar 21	Jun 8	245
6	2023	Republic	Hastings	Udic Argiustolls	Corn	Nov 22	Mar 21	Jun 8	286
7	2023	Shawnee	Eudora	Fluventic Hapludolls	Corn	Nov 23	Mar 14	May 2	127
8	2023	Franklin	Woodson	Abruptic Argiaquolls	Corn	Nov 25	Mar 30	May 19	-
9	2023	Reno	Nalim	Udic Argiustolls	Corn	Nov 21	Mar 8	May 22	314

[a] Triticale was not planted in 2022.
[b] Sites 1, 3, 4, and 8 did not have supplemental irrigation.

Table 2.2. Average soil test values before fertilizer application.

Site	pH	SOM	STP-M3	K	Clay	Sand
		$g\ kg^{-1}$	----- $mg\ kg^{-1}$ -----		------ % ------	
1	5.7	27	16.8	169	20	19
2	5.8	37	2.8	328	18	15
3	5.3	33	78.8	410	21	15
4	7.1	22	8.8	180	22	11
5	6.1	33	2.8	335	24	10
6	5.9	25	6.5	391	34	10
7	6.5	16	9.5	174	11	29
8	6.0	31	4.5	115	24	8
9	6.8	19	17.8	239	19	52

Abbreviations: SOM, Soil Organic Matter; STP-M3, Soil Test Phosphorus Mehlich-3.

Table 2.3. Cover crop biomass (kg ha^{-1}) with and without fertilizer application for individual and across sites in 2022 and 2023, and level of significance (p-values) for the effects of fertilizer application and cover crop (CC) treatments.

Effect	Treatments	Sites									Average by year	
		1	2	3	4	5	6	7	8	9	2022	2023
		kg ha^{-1}										
Fertilizer (kg ha^{-1})	0	1553	2819	1463	899 b	2698 b	2491	280 b	1126	3031	1945 b	1731 b
	45	1596	3841	1942	2176 a	4294 a	3190	412 a	1472	2891	2460 a	2429 a
CC	Oat	- [a]	-	-	1008 b	3129 b	2572	287	108 b	2554 b	-	1610 b
	Triticale	-	-	-	2067 a	3863 a	3109	405	2490 a	3368 a	-	2550 a
Fertilizer x CC	0 : Oat	-	-	-	622 c	2743 c	2424	173	102	2337 c	-	1400 c
	45 : Oat	-	-	-	1394 b	3515 b	2719	400	115	2772 bc	-	1819 bc
	0 : Triticale	-	-	-	1175 b	2653 c	2558	386	2150	3445 a	-	2061 b
	45 : Triticale	-	-	-	2958 a	5072 a	3661	425	2830	3290 ab	-	3040 a
		p-values										
Fertilizer		0.826	0.101	0.101	<0.001	<0.001	0.051	0.034	0.094	0.293	0.012	<0.001
CC		-	-	-	<0.001	<0.001	0.117	0.053	<0.001	<0.001	-	<0.001
Fertilizer x CC		-	-	-	0.001	<0.001	0.226	0.115	0.105	0.044	-	0.045

Within each column and for each factor, different letters denote statistically significant differences at the $p < 0.05$ level.

[a] The dashes (-) in the table indicate that only one cover crop (CC) was applied in 2022.

Table 2.4. Soil moisture content at soybean planting for individual and across sites in 2023 under different cover crop treatments with and without phosphorous fertilization, measured at a depth of 0-12 cm, and level of significance (p-values) for the effects of fertilizer application and cover crop (CC) treatments.

Effect	Treatments	Sites						Average by year
		4	5	6	7	8	9	2023
		---------- $cm^3\ cm^{-3}$ ----------						
Fertilizer (kg ha^{-1})	0	0.25 b	0.19	0.23	0.18	0.18	0.12	0.19
	45	0.26 a	0.19	0.20	0.18	0.18	0.13	0.19
CC	No CC	0.24 b	0.31 a	0.33 a	0.17	0.20	0.13	0.23
	Oat	0.27 a	0.11 b	0.17 b	0.18	0.18	0.13	0.16
	Triticale	0.26 a	0.14 b	0.14 b	0.18	0.18	0.12	0.18
Fertilizer x CC	0 : No CC	0.24	0.30	0.34	0.17	0.20	0.12	0.23
	45 : No CC	0.24	0.33	0.32	0.18	0.19	0.14	0.23
	0 : Oat	0.26	0.11	0.16	0.18	0.17	0.13	0.17
	45 : Oat	0.28	0.10	0.13	0.18	0.19	0.13	0.17
	0 : Triticale	0.25	0.15	0.18	0.18	0.17	0.12	0.17
	45 : Triticale	0.28	0.13	0.16	0.18	0.18	0.13	0.17
		---------- p-values ----------						
Fertilizer		0.003	0.988	0.059	0.808	0.788	0.463	0.986
CC		<0.001	<0.001	<0.001	0.570	0.098	0.943	<0.001
Fertilizer x CC		0.090	0.193	0.939	0.790	0.284	0.816	0.942

Within each column and for each factor, different letters denote statistically significant differences at the $p < 0.05$ level.

Table 2.5. Soil moisture after soybean harvest for individual and across sites in 2022 and 2023 under different cover crop treatments with and without phosphorous fertilization, measured at a depth of 0-12 cm, and level of significance (p-values) for the effects of fertilizer application and cover crop (CC) treatments.

Effect	Treatments	Sites								Average by year	
		1	2	3	4	5	6	8	9	2022	2022
		---------- cm^3 cm^{-3} ----------									
Fertilizer (kg ha^{-1})	0	0.33	0.27	0.22 a	0.29	0.31	0.35	0.34	0.22	0.27 a	0.30
	45	0.33	0.25	0.20 b	0.29	0.32	0.37	0.33	0.23	0.26 b	0.31
CC	No CC	0.33	0.24 b	0.21	0.30	0.31	0.36	0.34	0.22	0.26	0.31
	Oat	0.32	0.28 a	0.21	0.29	0.32	0.36	0.33	0.23	0.27	0.31
	Triticale	- [a]	-	-	0.28	0.31	0.35	0.33	0.23	-	0.30
Fertilizer x CC	0 : No CC	0.33	0.25	0.23	0.30	0.30	0.36	0.33	0.21	0.27	0.30
	45 : No CC	0.33	0.24	0.19	0.29	0.33	0.36	0.32	0.24	0.26	0.31
	0 : Oat	0.32	0.29	0.22	0.30	0.32	0.37	0.34	0.23	0.28	0.31
	45 : Oat	0.32	0.27	0.20	0.29	0.32	0.32	0.33	0.23	0.26	0.31
	0 : Triticale	-	-	-	0.28	0.31	0.36	0.34	0.23	-	0.30
	45 : Triticale	-	-	-	0.29	0.31	0.39	0.35	0.22	-	0.31
		---------- p-values ----------									
Fertilizer		0.976	0.082	0.020	0.803	0.528	0.519	0.552	0.691	0.038	0.579
CC		0.056	0.002	0.956	0.632	0.876	0.909	0.117	0.968	0.347	0.917
Fertilizer x CC		0.995	0.620	0.600	0.897	0.735	0.387	0.684	0.670	0.955	0.693

Within each column and for each factor, different letters denote statistically significant differences at the $p < 0.05$ level. Soil moisture data post-harvest was not collected at site 7.

[a] The dashes (-) in the table indicate that only one cover crop (CC) was applied in 2022.

Table 2.6. Cover crop phosphorus uptake with and without fertilizer application for individual and across sites in 2022 and 2023, and level of significance (p-values) for the effects of fertilizer application and cover crop (CC) treatments.

Effect	Treatments	Sites									Average by year	
		1	2	3	4	5	6	7	8	9	2022	2023
		---- kg ha^{-1} ----										
Fertilizer (kg ha^{-1})	0	2.67	4.23	4.74	1.38 b	4.07 b	6.14	0.66 b	2.16 b	6.90 b	3.88 b	3.55 b
	45	3.19	7.03	5.68	4.90 a	8.46 a	8.11	1.48 a	3.06 a	8.53 a	5.29 a	5.76 a
CC	Oat	- [a]	-	-	2.35 b	5.98	6.27	0.94	0.33 b	7.96	-	3.97 b
	Triticale	-	-	-	3.94 a	6.56	7.98	1.21	4.88 a	7.47	-	5.34 a
Fertilizer x CC	0 : Oat	-	-	-	0.79	4.31 b	5.66	0.37	0.29 c	6.75	-	3.03
	45 : Oat	-	-	-	3.90	7.61 a	6.88	1.50	0.39 c	9.17	-	4.92
	0 : Triticale	-	-	-	1.97	3.84 b	6.63	0.96	4.03 b	7.04	-	4.08
	45 : Triticale	-	-	-	5.92	9.27 a	9.34	1.47	5.73 a	7.90	-	6.60
		---- p-values ----										
Fertilizer		0.300	0.108	0.166	<0.001	<0.001	0.083	<0.001	0.024	0.012	0.011	<0.001
CC		-	-	-	<0.001	0.192	0.124	0.109	<0.001	0.372	-	<0.001
Fertilizer x CC		-	-	-	0.105	0.030	0.480	0.080	0.040	0.167	-	0.340

Within each column and for each factor, different letters denote statistically significant differences at the $p < 0.05$ level.

[a] The dashes (-) in the table indicate that only one cover crop (CC) was applied in 2022.

Table 2.7. Soybean phosphorus uptake at the V4 growth stage for individual and across sites in 2022 and 2023 under different cover crop treatments with and without phosphorous fertilization, and level of significance (p-values) for the effects of fertilizer application and cover crop (CC) treatments.

Effect	Treatments	Sites									Average by year	
		1	2	3	4	5	6	7	8	9	2022	2023
		kg ha^{-1}										
Fertilizer (kg ha^{-1})	0	1.16 b	0.42	0.60	2.84 b	1.73 b	1.00	1.15	1.12	3.17	0.73 b	1.83 b
	45	1.37 a	0.49	0.59	3.39 a	2.45 a	1.22	1.29	1.33	3.37	0.82 a	2.17 a
CC	No CC	1.41 a	0.64 a	0.63	3.34 a	2.34	1.39 a	1.49 a	1.16	3.84	0.89 a	2.26 a
	Oat	1.12 b	0.26 b	0.56	3.22 ab	2.10	0.84 b	1.08 b	1.37	3.04	0.65 b	1.94 b
	Triticale	- [a]	-	-	2.78 b	1.83	1.09 ab	1.07 b	1.15	2.95	-	1.81 b
Fertilizer x CC	0 : No CC	1.28	0.56	0.63	3.01	1.73	1.20	1.24 ab	0.86	3.64	0.82	1.95
	45 : No CC	1.54	0.72	0.63	3.67	2.96	1.59	1.75 a	1.47	4.03	0.96	2.58
	0 : Oat	1.04	0.28	0.57	2.85	1.83	0.89	1.05 b	1.32	3.20	0.63	1.86
	45 : Oat	1.20	0.26	0.55	3.59	2.37	0.80	1.11 b	1.41	2.87	0.67	2.03
	0 : Triticale	-	-	-	2.66	1.64	0.91	1.15 b	1.18	2.68	-	1.70
	45 : Triticale	-	-	-	2.90	2.02	1.27	0.99 b	1.12	3.22	-	1.92
		p-values										
Fertilizer		<0.001	0.424	0.764	0.006	0.005	0.164	0.153	0.133	0.509	0.043	<0.001
CC		<0.001	0.001	0.115	0.042	0.188	0.030	0.003	0.353	0.051	<0.001	<0.001
Fertilizer x CC		0.209	0.314	0.818	0.460	0.263	0.380	0.027	0.129	0.449	0.260	0.053

Within each column and for each factor, different letters denote statistically significant differences at the $p < 0.05$ level.

[a] The dashes (-) in the table indicate that only one cover crop (CC) was applied in 2022.

Table 2.8 Soybean trifoliate phosphorus concentration at the R3 growth stage for individual and across sites in 2022 and 2023 under different cover crop treatments with and without phosphorous fertilization, and level of significance (p-values) for the effects of fertilizer application and cover crop (CC) treatments.

Effect	Treatments	Sites									Average by year	
		1	2	3	4	5	6	7	8	9	2022	2023
		---------- g kg^{-1} ----------										
Fertilizer (kg ha^{-1})	0	3.9	3.8 b	4.0	3.0 b	3.2 b	3.6 b	3.9	3.6 b	3.4	3.9 b	3.5 b
	45	4.1	4.3 a	4.2	3.2 a	3.8 a	3.9 a	4.1	3.9 a	3.5	4.2 a	3.7 a
CC	No CC	4.0	4.0	4.0	3.2 a	3.8 a	3.6	4.0	3.7	3.4	4.0	3.6
	Oat	4.0	4.0	4.2	3.0 b	3.4 b	3.8	3.9	3.7	3.4	4.1	3.5
	Triticale	- [a]	-	-	3.0 ab	3.4 b	3.8	4.2	3.9	3.5	-	3.6
Fertilizer x CC	0 : No CC	3.9	3.8	3.9	3.1	3.6	3.3	4.0	3.7	3.4	3.8	3.5
	45 : No CC	4.2	4.3	4.2	3.2	4.0	3.8	4.1	3.8	3.4	4.2	3.7
	0 : Oat	3.9	3.8	4.2	2.9	3.1	3.7	3.7	3.5	3.3	4.0	3.4
	45 : Oat	4.1	4.3	4.2	3.1	3.7	4.0	4.1	3.8	3.5	4.2	3.7
	0 : Triticale	-	-	-	2.9	3.0	3.7	4.1	3.6	3.5	-	3.5
	45 : Triticale	-	-	-	3.2	3.7	3.8	4.2	4.1	3.5	-	3.8
		---------- p-values ----------										
Fertilizer		0.147	0.008	0.059	<0.001	<0.001	0.006	0.223	<0.001	0.869	0.016	<0.001
CC		0.761	0.908	0.124	0.033	<0.001	0.106	0.344	0.095	0.720	0.719	0.287
Fertilizer x CC		0.547	0.866	0.103	0.134	0.239	0.243	0.682	0.283	0.763	0.447	0.629

Within each column and for each factor, different letters denote statistically significant differences at the $p < 0.05$ level.

[a] The dashes (-) in the table indicate that only one cover crop (CC) was applied in 2022.

Table 2.9. Soybean phosphorus uptake at the R6 growth stage for individual and across sites in 2022 and 2023 under different cover crop treatments with and without phosphorous fertilization, and level of significance (p-values) for the effects of fertilizer application and cover crop (CC) treatments.

Effect	Treatments	Sites									Average by year	
		1	2	3	4	5	6	7	8	9	2022	2023
		kg ha^{-1}										
Fertilizer (kg ha^{-1})	0	30.5 b	21.0	30.2	24.9	17.7 b	18.3 b	28.9	9.03 b	27.9	27.2 b	21.1 b
	45	35.4 a	28.4	32.0	25.9	23.7 a	25.3 a	32.6	12.9 a	26.2	31.9 a	24.4 a
CC	No CC	32.3	25.5	32.7	26.2	22.4	21.6	31.0	9.9	25.4	30.2	22.8
	Oat	33.6	23.9	29.5	25.7	21.5	22.3	29.8	10.5	28.5	29.0	23.0
	Triticale	- [a]	-	-	24.3	18.3	21.4	31.5	12.5	27.2	-	22.5
Fertilizer x CC	0 : No CC	31.3	21.4	29.0	26.4	18.6	16.1	30.2	7.5	20.5	27.2	19.9
	45 : No CC	33.3	29.5	36.5	26.0	26.2	27.2	31.8	12.4	30.3	33.1	25.7
	0 : Oat	29.8	20.5	31.4	23.0	19.0	20.9	27.9	9.9	31.4	27.2	22.1
	45 : Oat	37.4	27.2	27.5	28.3	23.9	23.7	31.6	11.0	25.6	30.7	24.0
	0 : Triticale	-	-	-	25.2	15.4	17.8	28.4	9.7	31.7	-	21.4
	45 : Triticale	-	-	-	23.4	21.1	25.0	34.5	15.3	22.7	-	23.7
		p-values										
Fertilizer		0.035	0.056	0.539	0.717	0.003	0.019	0.198	0.007	0.530	0.010	0.003
CC		0.537	0.645	0.288	0.842	0.154	0.958	0.880	0.236	0.640	0.487	0.929
Fertilizer x CC		0.182	0.836	0.080	0.562	0.798	0.459	0.811	0.296	0.023	0.490	0.284

Within each column and for each factor, different letters denote statistically significant differences at the $p < 0.05$ level.

[a] The dashes (-) in the table indicate that only one cover crop (CC) was applied in 2022.

Table 2.10. Soybean phosphorus uptake in the seeds post-harvest for individual and across sites in 2022 and 2023 under different cover crop treatments with and without phosphorous fertilization, and level of significance (p-values) for the effects of fertilizer application and cover crop (CC) treatments.

Effect	Treatments	Sites									Average by year	
		1	2	3	4	5	6	7	8	9	2022	2023
		kg ha^{-1}										
Fertilizer (kg ha^{-1})	0	29.4	19.6	18.7	22.1	14.2 b	16.5 b	21.6	12.9	17.3	22.6	17.5 b
	45	28.4	20.0	18.3	23.6	17.5 a	19.0 a	23.3	13.9	16.8	22.2	19.0 a
CC	No CC	28.6	21.2 a	17.6 b	23.9	16.4	16.2	22.9	12.7	17.8	22.5	18.3
	Oat	29.2	18.4 b	19.4 a	22.6	16.2	18.1	22.6	14.3	17.0	22.3	18.5
	Triticale	- [a]	-	-	22.1	15.0	18.9	21.8	13.2	16.5	-	17.9
Fertilizer x CC	0 : No CC	28.8	20.2	18.1	23.3	15.7	14.0	21.9	12.1	16.9	22.4	17.3
	45 : No CC	28.4	22.1	17.1	24.5	17.1	18.3	24.0	13.3	18.6	22.5	19.3
	0 : Oat	30.0	18.9	19.3	20.9	14.4	17.2	21.9	13.6	17.6	22.7	17.6
	45 : Oat	28.5	17.9	19.5	24.3	18.1	18.9	23.4	14.9	16.3	22.0	19.3
	0 : Triticale	-	-	-	22.3	12.6	18.2	21.2	13.0	17.6	-	17.5
	45 : Triticale	-	-	-	22.0	17.4	19.7	22.4	13.5	15.4	-	18.4
		p-values										
Fertilizer		0.188	0.726	0.566	0.171	<0.001	0.030	0.199	0.485	0.656	0.636	0.002
CC		0.362	0.046	0.023	0.375	0.252	0.118	0.727	0.661	0.689	0.869	0.659
Fertilizer x CC		0.502	0.258	0.340	0.365	0.173	0.470	0.948	0.972	0.395	0.521	0.642

Within each column and for each factor, different letters denote statistically significant differences at the $p < 0.05$ level.

[a] The dashes (-) in the table indicate that only one cover crop (CC) was applied in 2022.

Table 2.11. Soybean seed yield response for individual and across sites in 2022 and 2023 under different cover crop treatments with and without phosphorous fertilization, and level of significance (p-values) for the effects of fertilizer application and cover crop (CC) treatments.

Effect	Treatments	Sites									Average by year	
		1	2	3	4	5	6	7	8	9	2022	2023
		kg ha^{-1}										
Fertilizer (kg ha^{-1})	0	4969	4441	3352	4498	3714 b	3754	5199	2744	3176	4254	3848
	45	4856	4530	3173	4315	4231 a	3957	5391	2872	2961	4186	3954
CC	No CC	4825	4784 a	3123	4555	3925	3600	5347	2567	3174	4244	3861
	Oat	4999	4187 b	3402	4347	4122	3904	5450	2951	3063	4196	3973
	Triticale	- [a]	-	-	4318	3871	4062	5087	2905	2968	-	3869
Fertilizer x CC	0 : No CC	4851	4625	3256	4515	3794	3446	5083	2384	3151	4244	3729
	45 : No CC	4800	4943	2989	4595	4055	3753	5611	2751	3197	4244	3994
	0 : Oat	5087	4258	3448	4314	3844	3896	5366	2956	3192	4264	3928
	45 : Oat	4911	4117	3357	4380	4400	3912	5534	2947	2933	4128	4018
	0 : Triticale	-	-	-	4666	3505	3920	5146	2892	3184	-	3886
	45 : Triticale	-	-	-	3969	4237	4204	5028	2918	2753	-	3851
		p-values										
Fertilizer		0.168	0.549	0.218	0.347	<0.001	0.216	0.334	0.619	0.227	0.507	0.187
CC		0.047	0.002	0.069	0.548	0.080	0.081	0.313	0.417	0.627	0.639	0.451
Fertilizer x CC		0.430	0.140	0.531	0.193	0.122	0.707	0.411	0.800	0.527	0.507	0.316

Within each column and for each factor, different letters denote statistically significant differences at the $p < 0.05$ level.

[a] The dashes (-) in the table indicate that only one cover crop (CC) was applied in 2022.

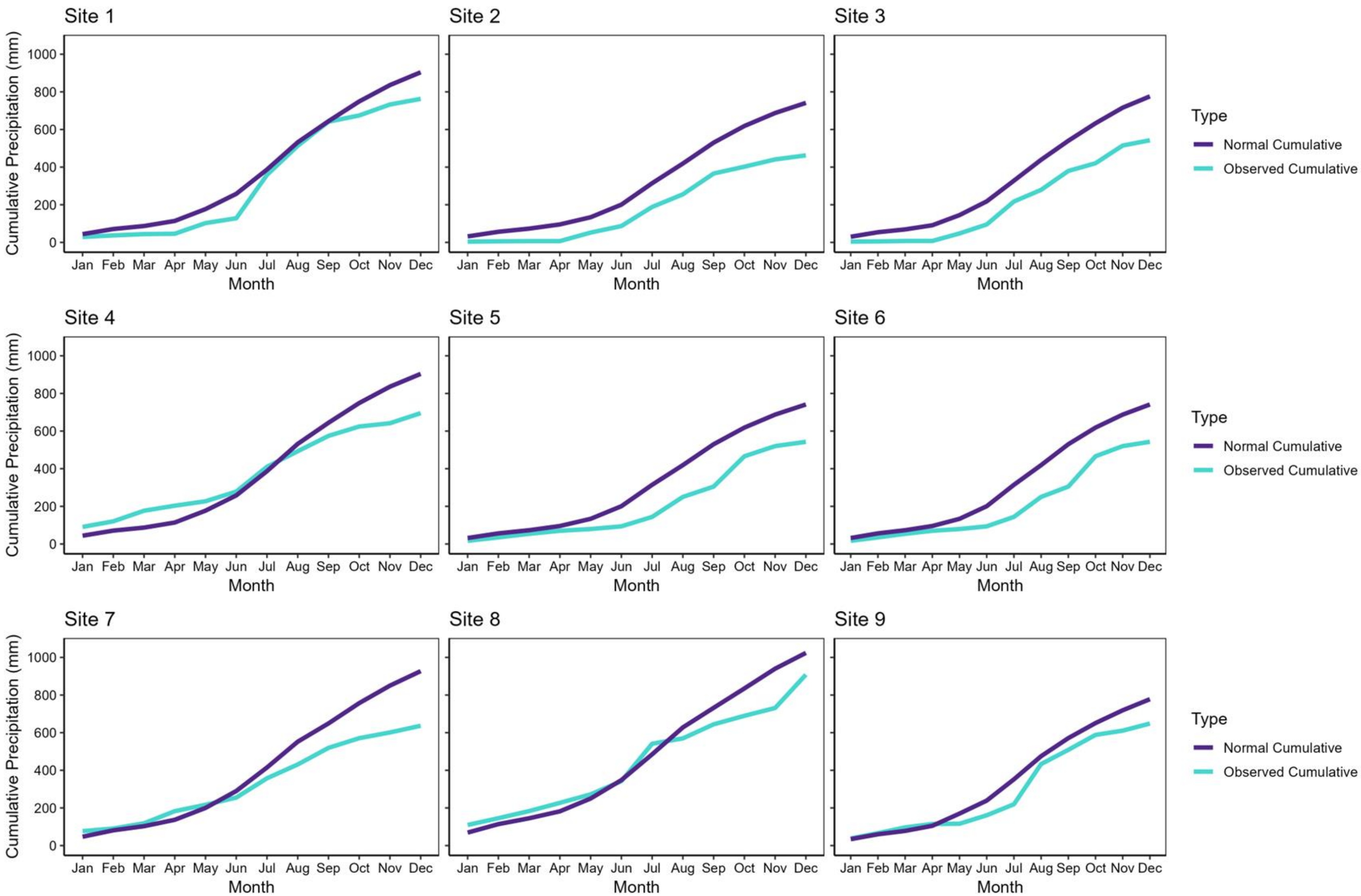

Figure 2.1. Normal and observed cumulative precipitation (mm) for the nine study site-years.

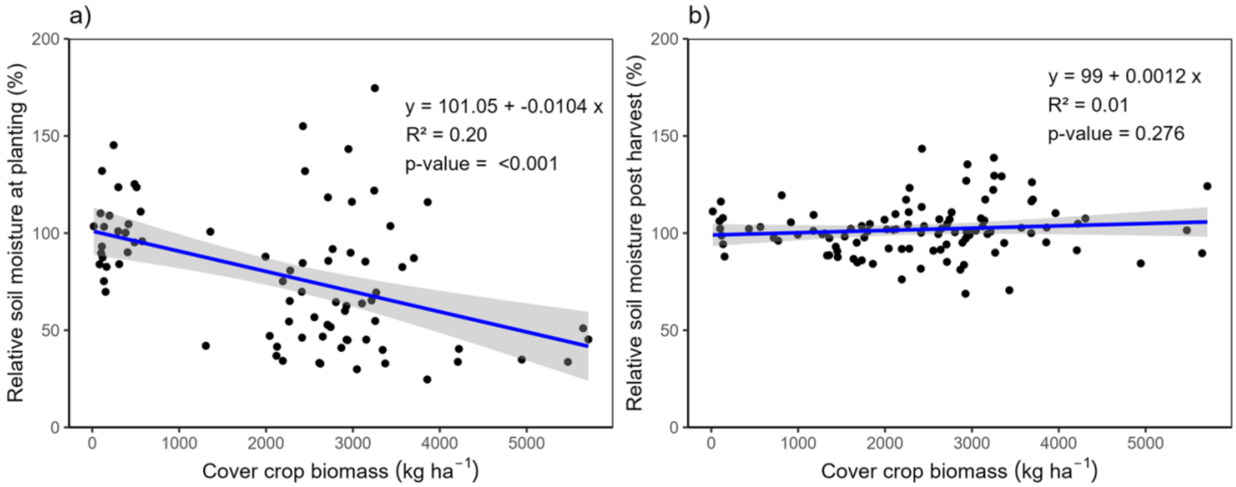

Figure 2.2. Relationship between cover crop biomass and relative soil moisture at a) planting and b) post-harvest of the soybean crop. Relative soil moisture was calculated by dividing the moisture content from plots with cover crop by the moisture content from plots without cover crops. All values are expressed as percentages by multiplying by 100. Soil moisture content was measured at a depth of 0-12 cm.

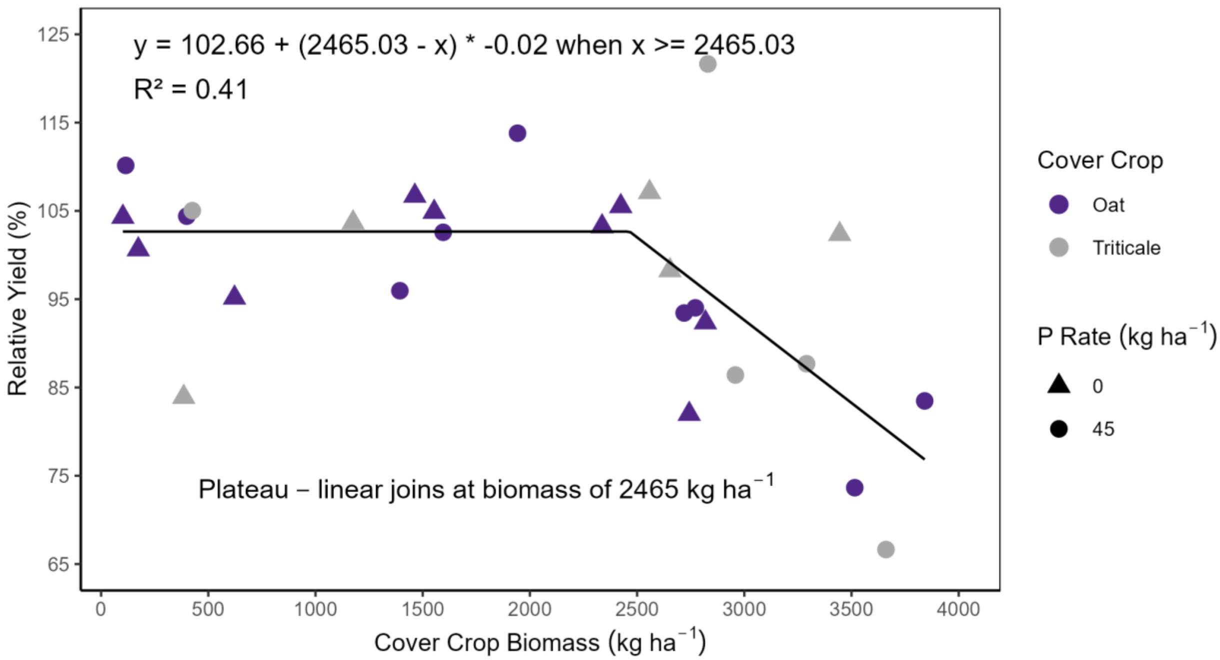

Figure 2.3. Plateau-linear relationship of the impact of cover crop biomass on soybean relative yield. Relative yield was calculated by dividing the seed yield from plots with cover crop by the seed yield from plots without cover crops. All values are expressed as percentages by multiplying by 100.

Chapter 3 - Evaluation of Soybean Response to Phosphorus Fertilizer Placement and Rates

Abstract

Optimizing phosphorus (P) fertilization techniques is crucial for improving P use efficiency and reducing environmental impacts in soybean [*Glycine max (L.)*] production. This study evaluated the impact of P fertilizer placement and rates on soybean growth and yield across nine locations in Kansas. This research compared subsurface and broadcast P applications at varying rates (45, 90, and 135 kg ha^{-1}) to assess their effects on P uptake, nutrient concentration, and seed yield. In early season analysis at the V4 soybean growth stage, subsurface placement generally enhanced P uptake compared to broadcast application, particularly in soils with low soil test phosphorus – Mehlich-3 (STP-M3) values. However, as the soybean season progressed to the R6 growth stage, the benefits of subsurface placement diminished, with no significant differences observed in P uptake or seed yield between the placement treatments. Seed yield analysis showed significant responses to fertilizer applications at only two sites. Overall, subsurface placement can improve early-season P uptake in low-P soils, but it does not translate into significant yield increases later in the season. These findings highlight the need to align P application rates with soil P levels and suggest that further research into the environmental benefits of subsurface placement, such as reduced P runoff, could be valuable for sustainable agricultural practices.

Introduction

The United States produced more than 116 million metric tons of soybeans, being the second-largest producer in the world in 2023, with Brazil as the largest producer with 156 million metric tons (USDA 2023). To support this production, fertilization techniques are necessary to reduce losses and improve fertilizer use efficiency.

The dependence on chemical phosphate fertilizers and limited reserves represents a critical vulnerability of current agricultural production, which requires technologies and crop management strategies to improve fertilizer use and efficiency (Penuelas et al. 2023). Hypothetical scenarios without replenishment of phosphorus (P) fertilizers result in a negative nutrient balance worldwide, emphasizing the need to minimize runoff losses for sustainable P management and avoid fertilizer depletion (Alewell et al. 2020).

Excessive application of P often results in environmental problems and a decline in water quality. This is primarily attributed to the acceleration of eutrophication, a process exacerbated by P runoff into water bodies when inappropriately managed in agriculture or applied excessively (Haque 2021).

To maximize P use efficiency, a more sustainable approach to fertilizer application might be to target the plant's demand for P more than the soil, and this would consider applying the fertilizer closer to the root (subsurface) rather than spreading the fertilizer over the entire soil surface (broadcast) (Withers et al. 2014). Broadcast fertilization can be an efficient way to apply P to soybeans; however, yields are similar when smaller doses are applied in-furrow (Rosolem and Merlin 2014). Subsurface application concentrates P in a small volume of soil compared to broadcast application, and places P beneath the zone where soil and water runoff interact, reducing losses of soluble, bioavailable, or total P compared to broadcast methods (Kimmell et al. 2001). Smith et al. (2016) found that applying P fertilizer below the soil surface resulted in a nearly 97% reduction in the overall P runoff compared to broadcasting on the surface.

Soybeans generally show minimal response to P application when soil P levels are high (Mallarino and Borges 2005). When the level of P in the soil is low, Cihacek et al., (1991) found that the yield response depended more on whether P was applied rather than the method of application. According to Rosa et al., (2020), P band applications optimize fertilizer in the early stages of soybean growth, while broadcast treatments improved fertilization efficiency during the reproductive stage of soybean development, although yields were not affected by placement in their results. Hansel et al. (2017) found that band application significantly increased both P uptake and P concentration in the soybean seeds. Under deep band application of P and K treatments, soybean yield increased compared to broadcast in soils with low P and K levels, as observed in a study by Hairston et al. (1990). Broadcast application, while more convenient to apply, may result in reduced height of plants and soybean yield, particularly in soils with high P fixation capacity (Barbosa et al. 2018). Consequently, in those situations, producers may have to apply higher rates of P to achieve the desired yield. In contrast, a study evaluating the placement of limestone alongside fertilizer treatments found that broadcast P application with lime led to higher soybean yields compared to deep band applications (Lutz and Jones 1974).

The objective of this study was to comprehensively assess the impact of P fertilizer placement on various key parameters, including soybean aboveground dry weight, nutrient uptake, seed yield, and seed nutrient concentration in the state of Kansas.

Materials and Methods

Three soybean sites were established in 2022 and six in 2023. A description of each site is presented in Table 3.1. Row spacing was 76 cm; plot size was 12.2 m in length and 3 m in width (36.6 m^2) – in all sites.

The experimental design was a randomized complete block design with four replications and the treatment structure was a 3x2 factorial plus a control. Fertilizer treatments consisted of a control without fertilizer application, three subsurface treatments with rates of 45, 90, and 135 kg ha^{-1}, and broadcast treatments with the same rates as applied in subsurface. Broadcast and subsurface sources were monoammonium phosphate (MAP) (11-52-0). Sub-surface fertilizer was applied 5-10 cm deep and 15 cm in space between rows, 7-10 weeks before planting using a drill. Broadcast treatments were applied by hand simultaneously with the subsurface treatments.

A composite soil sample of 15 cores was collected from each replication (block) for soil characterization before the establishment of the study. The soil samples underwent a sequential process for analysis. Initially, they were air-dried at 40 ^oC, followed by sieving through a 2 mm mesh. Subsequently, the processed samples were stored in plastic vials for analysis. Extractable P was quantified utilizing the Mehlich-3 method, as described by Frank, Beegle, and Denning (1998). The resulting extracts underwent colorimetric analysis. Soil organic matter (SOM) content was determined through loss in ignition (Combs and Nathan 1998). The pH levels were measured using a 1:1 ratio of soil to water, following the procedure detailed by (Watson and Brown 1998).

The study sites encompassed a diverse range of soil conditions (Table 3.2). Soil pH varied from 5.3 at Site 3, the lowest, to 7.1 at Site 4, the highest. Soil organic matter (SOM) ranged from 16 g kg^{-1} at Site 7 to 37 g kg^{-1} at Site 2. Most sites had soil test phosphorus levels

(STP-M3) between 2.8 mg kg^{-1} at Site 2 and 17.8 mg kg^{-1} at Site 9, with Site 3 standing out for its notably high STP-M3 level of 78.8 mg kg^{-1}. Clay content was highest at Site 6 (34%) and lowest at Site 7 (11%), while sand content ranged from a high of 52% at Site 9 to a low of 8% at Site 8.

Soybean tissue samples were taken during the vegetative and reproductive growth stages. Whole plant samples were taken in the V4 (four trifoliate fully developed) and R6 (seed contains a green seed that fills the cavity in one of the four uppermost nodes on the main stem) growth stages. Trifoliate samples were taken in the R3 growth stage (pods are 4.76 mm long on one of the four uppermost nodes on the main stem with fully developed leaf). The V4 growth stage sampling was accomplished by removing fifteen soybean plants at random from non-harvest rows of each plot. For the R3 growth stage, sampling was done by collecting thirty trifoliate leaves from the top of the plants at random from harvest rows of each plot. For the R6 growth stage, the sampling was accomplished by removing six soybean plants at random from the harvest rows of each plot. Plant samples were dried in a forced air oven at 60 ^{0}C for a minimum of six days and the whole plant samples (V4 and R6) were weighed for biomass calculation. Once dry and weighed, plants were ground to pass through a 2mm sieve and then analyzed for total P content using the sulfuric peroxide digest as described by (Lindner and Harley 1942). The total P was determined using an inductively coupled plasma (ICP) spectrometer (720-ES ICP; Varian Australia Pty Ltd, Mulgrave, Victoria, Australia). The product of P concentration and biomass was used to quantify total P uptake at the V4 and R6 growth stages.

A Wintersteiger combine (Wintersteiger Inc. – headquartered in Salt Lake City, Utah, USA), fitted with a 1.4-meter head was used to quantify soybean seed yield. The two central rows of each plot were harvested totalizing an area of 18.58 m^2. Seed weight was recorded, and subsamples were taken from each plot and analyzed for moisture using a Dickey-John GAC-2500-AGRI seed analysis computer (DICKEY-john Corp – headquartered in Auburn, Illinois, USA). Seed yield was calculated adjusting the moisture to 13%. The seeds were ground and analyzed for P content using the same methodology as the tissue samples.

Data were analyzed by site and combined using the lme4 package in R 4.3.0, using RStudio (Version 2023.06.1+524) assuming block as a random factor in the Analysis of Variance. When sites were combined, sites were also considered as a random effect in the model. The t-tests use Kenward-Roger's method and the statistical significance was set at alpha < 0.05 (RStudio Team 2021).

Results and Discussion

Phosphorus uptake and concentration in tissue

In the V4 P uptake analysis of the nine sites harvested, four sites (1, 4, 5, and 6) showed significant responses to fertilizer application, with Site 3 showing a significant interaction between P rate and placement (Table 3.3). Across the nine sites, four sites showed significant response to fertilizer application, with the highest fertilizer rate showing the greatest P uptake with 2.67 kg ha^{-1}, when considering only the effect of fertilizer (Table 3.3). Treatments applied in subsurface resulted in soybean P uptake greater than broadcast both for responsive and nonresponsive sites compared to broadcast treatments at the V4 growth stage, even though there was no interaction between the effects of fertilizer rates and placements.

Sites responsive to P placement at the V4 growth stage (Sites 1, 4, 5, and 6) had STP-M3 values of 16.8, 8.8, 2.8, and 6.5 mg kg^{-1}, respectively (Table 3.2), showing that responsiveness was not limited to sites with the lowest STP-M3 levels. This suggests that factors other than soil

P levels may influence the P uptake response. One possible explanation for the increased P uptake observed at these responsive sites is the placement of P in the subsoil, which positioned the nutrient closer to the roots, making it more readily available for uptake at a critical growth stage. This placement effect could potentially interact with other site-specific factors, such as soil structure, root distribution, or moisture levels, that may facilitate greater P uptake.

Phosphorus concentration in the trifoliate at R3 was influenced by fertilizer application, with the highest concentration observed in the treatment receiving 135 kg ha^{-1} of fertilizer (4.4 g kg^{-1}) and the lowest in the 45 kg ha^{-1} treatment (3.6 g kg^{-1}) at sites responsive to fertilizer (Table 3.4). Fertilizer placement was also significant at these responsive sites, with broadcast applications resulting in a slightly higher P concentration of 0.1 g kg^{-1} when comparing to subsurface placement, although this difference is minor when biomass for total P uptake is not considered. At nonresponsive sites, there was no effect of placement, nor were there any interactions between rates and placements at either responsive or nonresponsive sites (Table 3.4). Examining the analysis of variance for trifoliate P concentration for each site (Table 3.4), it reveals that only one out of nine sites (Site 2) showed a significant response to placement, with no site exhibiting an interaction between fertilizer rate and placement.

The P uptake at the R6 stage did not show significant response to the treatments of fertilizer rate and placement (Table 3.5). A significant increase in P uptake to fertilizer rate was observed on the analysis of variance for the three responsive sites. For the three responsive sites, the treatment without fertilizer had a P uptake of 18.7 kg ha^{-1}, while among fertilizer rate treatments the uptake for the lowest rate was 27.6 kg ha^{-1}, and the highest was 35.2 kg ha^{-1}. Because the statistical analysis did not include the zero P rate, we cannot draw a definitive conclusion, but the lowest rate of P being applied (45 kg ha^{-1}) seems to be sufficient to increase the P uptake at the R6 growth stage in some of the sites.

Sucunza et al. (2018) found results for critical STP values that suggest the critical value using Bray-1 (STP-B1) for soybean to be around 14.3 mg P kg^{-1}, which is a close or higher value than five of our nine sites if we consider the conversion from STP-B1 to STP-M3 suggested by Roa-Acosta and Ruiz Diaz (2022) represented by the equation: $y = -1.22 + 1.08x$, where y is STP-M3 (mg kg^{-1}) and x is STP-B1 (mg kg^{-1}) (Table 3.2). This is likely why we had an increase in P uptake from the zero P rate to the treatments with fertilizer application on the analysis across sites. Looking at the analysis of variance of the individual sites, only one out of nine (Site 5) had a significant response to fertilizer rate, and none of them had a significant response to placement or to the interaction between P rate and placement (Table 3.5), reinforcing that there was no effect on soybean P uptake with higher P application rates in the late season.

The P uptake in seeds showed a similar pattern to that at the R6 growth stage, with no response to the interaction of fertilizer rate and placement (Table 3.6). However, when analyzed the responsive sites to fertilizer application, there was an increase in P uptake by the seeds and a significant response to placement ($p = 0.038$), where the treatments applied in broadcast showed an increase in P uptake of 1.28 kg ha^{-1} (Table 3.6). The analysis of variance of the individual sites showed a significant response to fertilizer rate (without control) in two out of nine sites (Site 2 with $p < 0.001$ and site 5 with $p = 0.009$) and to placement in site 2 ($p < 0.001$) (Table 3.6).

A meta-analysis by Nkebiwe et al. (2016) demonstrated that the subsurface placement of fertilizers significantly enhances nutrient uptake in the above-ground biomass and leads to increased soybean yield compared to the broadcast application, but phosphate (PO_4^{-3}) applied alone in subsurface without NH_4^+ or $CO(NH_2)_2$ did not show differences in yield or total uptake of the above-ground biomass compared to the broadcast application in multiple crops. In our study, we observed that in the early season at the V4 growth stage, the subsurface placement positively affected the P uptake in some sites. However, as the plants advanced to the R3 and R6 growth stages, the differences in P concentration and uptake between placements diminished.

Seed Yield

Two sites showed statistically significant yield responses to P fertilizer treatments at the 0.05 probability level (Table 3.7). Responsive locations had STP-M3 values of 2.8 mg kg^{-1} (Sites 2 and 5) (Table 3.2). Only site 3 showed a significant response to placement. When analyzed across locations, there was no significant response to fertilizer rate, placement, or to the interaction between fertilizer rate and placement on the nonresponsive sites, and the responsive sites did not have any effect of placement or interaction with fertilizer rate (Table 3.7). Overall, our results are consistent with those of Estigaribia et al. (2020), indicating that soybean development and productivity are not impacted by different P placement methods. According to Borges and Mallarino (2000), subsurface P placement is more effective than broadcast in reducing P losses as it keeps the nutrient in a smaller volume of soil and below the runoff zone. While subsurface placement of P did not show a late-season and seed yield advantage over broadcast application, its potential to reduce P contamination in surface water should be considered.

The sufficiency recommendation of P_2O_5 $acre^{-1}$ for Kansas developed by the Kansas State University, says that for an expected yield of 60 bushels $acre^{-1}$ (4035.1 kg ha^{-1}) in a very low STP-M3 (0-8 mg kg^{-1}), the amount of P_2O_5 to be applied should be 70 lb $acre^{-1}$ (78.5 kg ha^{-1}), in a low STP-M3 (9-15 mg kg^{-1}), the amount of P_2O_5 to be applied should be 35 lb $acre^{-1}$ (39.2 kg ha^{-1}), in a medium STP-M3 (16-20 mg kg^{-1}), the amount of P_2O_5 to be applied should be 15 lb acre^{-1} (16.8 kg ha^{-1}), and when STP-M3 is higher than 20 mg kg^{-1}, no P fertilizer application is required (Ruiz Diaz et al. 2024). In this study, four of the nine sites had a very low STP-M3 (Sites 2, 5, 6, and 8), two sites had a low STP-M3 (Sites 4 and 7), two sites had a medium STP-M3 (Sites 1 and 9), and Site 3 had an average STP-M3 of 78.8 mg kg^{-1} (Table 3.2). In most of the analyses across locations we observed that the zero fertilizer rate were below the treatment with the lowest fertilizer rate considered in the analysis (45 kg ha^{-1}), which probably explains the absence of statistical differences in the late season parameters, because five of our sites had fertilizer application higher than the sufficiency recommendation for Kansas, and the other four sites had an application of at least 57.3% of the recommended rate.

Conclusion

Subsurface P placement generally enhanced P uptake compared to broadcast application, particularly with low STP-M3 levels. However, as the growing season progressed, differences in P uptake between treatments diminished, and by the R6 growth stage, no significant advantages were observed for specific placement methods.

Seed yield analysis showed limited responsiveness to Fertilizer rate and placement, with only two sites demonstrating significant yield differences when increasing fertilizer rate. These sites had very low STP-M3 values, which aligns with established sufficiency recommendations for Kansas. The lack of significant yield response across most locations suggests that the P rates applied exceeded the requirements for maximizing yield, particularly in soils with medium to high STP-M3 values.

Overall, while subsurface placement can improve early season P uptake in low-P soils, its benefits in terms of P uptake do not translate into significant yield increases later in the season. These findings underscore the importance of aligning P application rates with soil P levels and highlight that higher rates or specific placements may not offer additional benefits for soybean production. Further research could explore the environmental benefits of subsurface placement, such as reducing P runoff, to support conservation-focused practices.

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Tables and Figures

Table 3.1. Study location, soil classification, previous crop, and planting date information.

				Soil Classification			
Site	Location	Year	County	Series	Subgroup	Previous Crop	Planting Date
1	Manhattan	2022	Riley	Reading	Pachic Argiudolls	Soybean	May 22nd
2	Scandia	2022	Republic	Crete	Pachic Udertic Argiustolls	Corn	Jun 13th
3	Belleville	2022	Republic	Crete	Pachic Udertic Argiustolls	Corn	May 20th
4	Manhattan	2023	Riley	Kennebec	Cumulic Hapludolls	Soybean	May 24th
5	Scandia South	2023	Republic	Crete	Pachic Udertic Argiustolls	Corn	Jun 8th
6	Scandia Headquarters	2023	Republic	Hastings	Udic Argiustolls	Corn	Jun 8th
7	Silver Lake	2023	Shawnee	Eudora	Fluventic Hapludolls	Corn	May 2nd
8	Ottawa	2023	Franklin	Woodson	Abruptic Argiaquolls	Corn	May 19th
9	Hutchinson	2023	Reno	Nalim	Udic Argiustolls	Corn	May 22nd

Table 3.2. Average soil test values before fertilizer application.

Site	pH	SOM	STP-M3	K	Clay	Sand
		$g\ kg^{-1}$	----- $mg\ kg^{-1}$ -----		------ % ------	
1	5.7	27	16.8	169	20	19
2	5.8	37	2.8	328	18	15
3	5.3	33	78.8	410	21	15
4	7.1	22	8.8	180	22	11
5	6.1	33	2.8	335	24	10
6	5.9	25	6.5	391	34	10
7	6.5	16	9.5	174	11	29
8	6.0	31	4.5	115	24	8
9	6.8	19	17.8	239	19	52

Abbreviations: SOM, Soil Organic Matter; STP-M3, Soil Test Phosphorus Mehlich-3.

Table 3.3. Soybean phosphorus (P) uptake at the V4 growth stages for individual, responsive and nonresponsive sites to fertilizer application under different fertilizer rates and fertilizer placements, and level of significance (p-values) for the effects of fertilizer rates and placement treatments.

		Sites									Average	
Effect	Treatments	1	2	3	4	5	6	7	8	9	Responsive (4) [a]	Nonresponsive (5)
		kg ha^{-1}										
Fertilizer (kg ha^{-1})	45	1.42	0.67	0.66	3.63	2.48	1.41	1.75 b	1.17	3.71	2.32 b	1.53
	90	1.60	0.68	0.68	4.11	2.80	1.83	1.75 b	1.19	3.80	2.63 ab	1.59
	135	1.49	0.72	0.65	4.14	2.49	1.85	2.21 a	1.09	4.15	2.67 a	1.62
Placement	Broadcast	1.37 b	0.64	0.69	3.59 b	2.13 b	1.40 b	2.02	1.01	3.68	2.23 b	1.48 b
	Subsurface	1.63 a	0.74	0.64	4.33 a	3.05 a	2.00 a	1.80	1.30	4.10	2.85 a	1.68 a
Fertilizer (kg ha^{-1}) x Placement	45 : Broadcast	1.29	0.62	0.70	3.59	1.99	1.24	1.75	0.87	3.39	2.14	1.37
	45 : Subsurface	1.54	0.72	0.63	3.67	2.96	1.59	1.75	1.47	4.03	2.49	1.68
	90 : Broadcast	1.46	0.67	0.63	3.52	2.46	1.38	1.58	1.08	3.77	2.23	1.52
	90 : Subsurface	1.74	0.70	0.74	4.70	3.15	2.29	1.94	1.31	3.84	3.02	1.67
	135 : Broadcast	1.36	0.62	0.76	3.66	1.94	1.57	2.06	1.07	3.87	2.31	1.54
	135 : Subsurface	1.61	0.81	0.54	4.63	3.05	2.12	2.36	1.11	4.42	3.04	1.70
		p-values										
Fertilizer		0.288	0.820	0.786	0.161	0.490	0.226	0.006	0.814	0.565	0.016	0.662
Placement		0.014	0.124	0.173	0.005	0.002	0.016	0.066	0.056	0.240	<0.001	0.019
Fertilizer x Placement		0.992	0.593	0.011	0.147	0.778	0.601	0.390	0.275	0.773	0.199	0.704

[a] Number of responsive and nonresponsive sites to fertilizer application. Sites were classified by significance ($p < 0.05$) from an analysis of variance across fertilizer rates, compared to the zero rate

Table 3.4. Soybean trifoliate phosphorus (P) concentration at the R3 growth stages for individual, responsive and nonresponsive sites to fertilizer application under different fertilizer rates and fertilizer placements, and level of significance (p-values) for the effects of fertilizer rates and placement treatments.

Effect	Treatments	Sites									Average	
		1	2	3	4	5	6	7	8	9	Responsive (5)[a]	Nonresponsive (4)
		g kg^{-1}										
Fertilizer (kg ha^{-1})	45	4.0	4.3 b	4.1	3.2	4.1 b	3.9	4.2	3.8 b	3.5	4.1 b	3.7
	90	4.2	4.7 a	4.1	3.3	4.2 ab	4.0	4.4	4.2 a	3.1	4.3 a	3.7
	135	4.1	4.9 a	4.1	3.3	4.3 a	4.2	4.4	4.2 a	3.2	4.4 a	3.7
Placement	Broadcast	4.1	4.7 a	4.0	3.3	4.3	4.1	4.4	4.1	3.4	4.3 a	3.7
	Subsurface	4.1	4.5 b	4.2	3.2	4.2	4.0	4.3	3.9	3.2	4.2 b	3.7
Fertilizer (kg ha^{-1}) x Placement	45 : Broadcast	3.9	4.4	3.9	3.2	4.1	4.0	4.3	3.7	3.5	4.1	3.7
	45 : Subsurface	4.2	4.3	4.2	3.2	4.0	3.8	4.1	3.8	3.4	4.0	3.7
	90 : Broadcast	4.2	4.7	4.2	3.4	4.3	4.1	4.4	4.4	3.2	4.4	3.7
	90 : Subsurface	4.1	4.6	4.1	3.2	4.2	3.9	4.5	4.0	3.0	4.3	3.6
	135 : Broadcast	4.1	5.0	3.9	3.4	4.4	4.2	4.5	4.3	3.3	4.5	3.7
	135 : Subsurface	4.1	4.7	4.3	3.2	4.3	4.1	4.4	4.0	3.0	4.3	3.7
		p-values										
Fertilizer		0.706	<0.001	0.891	0.465	0.030	0.250	0.104	0.015	0.109	<0.001	0.926
Placement		0.630	0.027	0.094	0.075	0.275	0.127	0.695	0.110	0.148	0.007	0.742
Fertilizer x Placement		0.308	0.318	0.308	0.686	0.927	0.714	0.265	0.223	0.854	0.905	0.488

[a] Number of responsive and nonresponsive sites to fertilizer application. Sites were classified by significance ($p < 0.05$) from an analysis of variance across fertilizer rates, compared to the zero rate.

Table 3.5. Soybean phosphorus (P) uptake at the R6 growth stages for individual, responsive and nonresponsive sites to fertilizer application under different fertilizer rates and fertilizer placements, and level of significance (p-values) for the effects of fertilizer rates and placement treatments.

Effect	Treatments	Sites									Average	
		1	2	3	4	5	6	7	8	9	Responsive (3)[a]	Nonresponsive (6)
		kg ha^{-1}										
Fertilizer (kg ha^{-1})	45	34.1	30.6	33.1	26.2	27.7 b	24.5	34.5	10.6	28.2	27.6 b	27.8
	90	35.1	30.0	32.0	30.9	35.6 ab	22.2	36.2	9.5	29.7	29.3 ab	28.9
	135	33.7	36.0	30.4	32.2	39.9 a	29.7	40.0	12.2	26.0	35.2 a	29.1
Placement	Broadcast	34.8	34.1	30.2	29.5	37.3	23.7	38.6	9.7	27.4	31.7	28.4
	Subsurface	33.7	30.3	33.5	30.0	31.5	27.3	35.2	11.8	28.6	29.7	28.8
Fertilizer (kg ha^{-1}) x Placement	45 : Broadcast	34.8	31.8	29.7	26.4	29.3	21.7	37.2	8.8	26.1	27.6	27.2
	45 : Subsurface	33.3	29.5	36.5	26.0	26.2	27.2	31.8	12.4	30.3	27.6	28.4
	90 : Broadcast	35.0	31.0	31.5	32.1	39.2	21.0	38.2	8.6	29.4	30.4	29.1
	90 : Subsurface	35.1	29.0	32.5	29.7	31.9	23.5	34.2	10.5	29.9	28.1	28.7
	135 : Broadcast	34.7	39.5	29.4	30.1	43.4	28.4	40.5	11.7	26.7	37.1	28.8
	135 : Subsurface	32.8	32.5	31.4	34.2	36.4	31.1	39.5	12.6	25.4	33.3	29.3
		p-values										
Fertilizer		0.803	0.284	0.793	0.173	0.024	0.072	0.448	0.236	0.429	0.012	0.573
Placement		0.522	0.267	0.318	0.865	0.093	0.175	0.340	0.097	0.606	0.348	0.703
Fertilizer x Placement		0.882	0.779	0.738	0.590	0.842	0.863	0.874	0.651	0.602	0.761	0.809

[a] Number of responsive and nonresponsive sites to fertilizer application. Sites were classified by significance ($p < 0.05$) from an analysis of variance across fertilizer rates, compared to the zero rate.

Table 3.6. Soybean seed phosphorus (P) uptake response for individual, responsive and nonresponsive sites to fertilizer application under different fertilizer rates and fertilizer placements, and level of significance (p-values) for the effects of fertilizer rates and placement treatments.

Effect	Treatments	Sites									Average	
		1	2	3	4	5	6	7	8	9	Responsive (2)[a]	Nonresponsive (7)
		---------- kg ha^{-1} ----------										
Fertilizer (kg ha^{-1})	45	28.3	22.5 b	17.9	24.0	17.8 b	18.3	24.5	11.8	18.0	20.1 b	20.4
	90	28.8	25.4 a	17.6	23.3	21.8 a	17.3	25.3	11.8	17.5	23.6 a	20.2
	135	28.6	26.9 a	17.6	26.4	20.7 ab	21.7	27.6	12.0	16.8	23.8 a	21.5
Placement	Broadcast	28.5	26.2 a	18.4	24.5	20.1	18.2	25.8	11.8	17.4	23.15 a	20.7
	Subsurface	28.6	23.7 b	17.0	24.6	20.0	20.1	25.8	12.0	17.5	21.87 b	20.8
Fertilizer (kg ha^{-1}) x Placement	45 : Broadcast	28.3	22.9	18.8	23.5	18.5	18.3	24.9	10.4	17.3	20.7	20.2
	45 : Subsurface	28.4	22.1	17.1	24.5	17.1	18.3	24.0	13.3	18.6	19.6	20.6
	90 : Broadcast	28.9	27.5	18.0	25.6	22.0	14.3	25.4	11.0	17.5	24.8	20.1
	90 : Subsurface	28.6	23.2	17.2	21.0	21.6	20.3	25.2	12.6	17.5	22.4	20.4
	135 : Broadcast	28.3	28.1	18.5	24.5	19.9	22.0	27.1	14.1	17.3	24.0	21.7
	135 : Subsurface	28.9	25.8	16.8	28.4	21.4	21.5	28.1	9.9	16.3	23.6	21.4
		---------- p-values ----------										
Fertilizer rate		0.828	<0.001	0.930	0.484	0.009	0.168	0.091	0.993	0.581	<0.001	0.163
Placement		0.871	0.001	0.068	0.964	0.895	0.335	0.969	0.929	0.915	0.038	0.839
Fertilizer x Placement		0.778	0.078	0.835	0.293	0.461	0.327	0.784	0.157	0.613	0.404	0.898

[a] Number of responsive and nonresponsive sites to fertilizer application. Sites were classified by significance ($p < 0.05$) from an analysis of variance across fertilizer rates, compared to the zero rate.

Table 3.7. Soybean seed yield response for individual sites, responsive and nonresponsive sites to fertilizer application under different fertilizer rates and fertilizer placements, and level of significance (p-values) for the effects of fertilizer rates and placement treatments.

Effect	Treatments	Sites									Average	
		1	2	3	4	5	6	7	8	9	Responsive (2)[a]	Nonresponsive (7)
		kg ha^{-1}										
Fertilizer (kg ha^{-1})	45	4819	4888 b	3152	4309	4048 b	3694	5569	2493	3084	4468 b	3874
	90	4931	4898 b	3132	4521	4308 a	4082	5225	2341	3059	4603 ab	3913
	135	4821	5171 a	3056	4449	4190 ab	4200	5777	2552	2884	4680 a	3962
Placement	Broadcast	4830	5028	3256 a	4243	4140	3935	5473	2329	3027	4584	3871
	Subsurface	4885	4944	2971 b	4609	4224	4050	5575	2595	2991	4584	3962
Fertilizer (kg ha^{-1}) x Placement	45 : Broadcast	4838	4834	3314	4022	4041	3635	5527	2235	2970	4437	3792
	45 : Subsurface	4800	4943	2989	4595	4055	3753	5611	2751	3197	4499	3957
	90 : Broadcast	4954	5041	3239	4514	4302	3905	5201	2240	3091	4671	3880
	90 : Subsurface	4908	4755	3026	4528	4314	4259	5250	2441	3026	4534	3946
	135 : Broadcast	4696	5209	3214	4194	4077	4264	5691	2512	3020	4643	3942
	135 : Subsurface	4945	5133	2898	4705	4302	4136	5863	2592	2749	4718	3982
		p-values										
Fertilizer rate		0.516	0.019	0.801	0.613	0.049	0.082	0.061	0.496	0.438	0.031	0.574
Placement		0.548	0.314	0.035	0.055	0.299	0.538	0.568	0.092	0.789	0.997	0.185
Fertilizer x Placement		0.332	0.171	0.919	0.404	0.459	0.577	0.957	0.477	0.340	0.323	0.732

[a] Number of responsive and nonresponsive sites to fertilizer application. Sites were classified by significance ($p < 0.05$) from an analysis of variance across fertilizer rates, compared to the zero rate.

Chapter 4 – General Conclusion

The research presented in this thesis evaluates the impact of cover crops and phosphorus fertilizer management on soybean growth, phosphorus uptake, and yield in Kansas. Through two studies, we examined the combined effect of cover crops and phosphorus fertilization on soybean productivity, soil moisture, and nutrient uptake, and compared the effectiveness of phosphorus fertilizer placement methods (broadcast vs. subsurface) at different rates.

The first study revealed that cover crops, particularly triticale, significantly increased cover crop biomass when fertilizer was applied. However, the increase in biomass also led to a reduction in soil moisture at the time of soybean planting, especially in regions with limited rainfall. This reduction in moisture presents a trade-off between biomass production and soil water availability. A critical threshold for cover crop biomass of 2465 kg ha^{-1} was identified, beyond which soybean seed yield began to decline. This finding emphasizes the importance of managing cover crop growth and termination timing to avoid yield penalties. Although cover crops improved phosphorus uptake from the soil, they competed with soybeans for phosphorus and water during the early growth stages, which reduced phosphorus uptake at the V4 growth stage. However, as the season progressed, the application of fertilizer enhanced phosphorus concentration in soybeans, and no significant interactions between cover crops and fertilization were observed in terms of their effects on soybean seed yield.

The second study focused on phosphorus fertilizer placement and its influence on soybean performance. Subsurface phosphorus placement was found to improve early-season phosphorus uptake, particularly in soils with low phosphorus availability. However, as the growing season progressed, the differences in phosphorus uptake between subsurface and broadcast application methods diminished. By the R6 growth stage, there were no significant differences in phosphorus uptake or seed yield between the different placement methods. Seed yield analysis showed limited responsiveness to phosphorus fertilization, with only two sites exhibiting significant differences, both of which had very low phosphorus levels. These findings suggest that in soils with medium to high phosphorus availability, the phosphorus application rates used in the study exceeded what was required to maximize yield, further highlighting the importance of aligning phosphorus application rates with the levels of phosphorus in the soil.

Overall, the findings from both studies underscore the need for tailored management practices for both cover crops and phosphorus fertilization. In regions with limited precipitation, the timing of cover crop termination is crucial to prevent soil moisture depletion, which can negatively impact soybean yields. Phosphorus application should also be aligned with soil phosphorus levels to avoid over-application, which does not enhance productivity but may contribute to environmental concerns, such as phosphorus runoff. While subsurface phosphorus placement can improve early-season phosphorus uptake in low-phosphorus soils, it does not translate into significant yield increases in most cases, especially as the season progresses.

These findings contribute to a better understanding of how to balance cover crop use and phosphorus management in soybean production systems. The research highlights the importance of managing cover crop growth to optimize soil health and soybean productivity, while also aligning phosphorus fertilizer rates with soil needs to enhance nutrient use efficiency and reduce environmental risks. Future research could focus on exploring the long-term environmental benefits of subsurface phosphorus placement, particularly its role in reducing phosphorus runoff, as well as further investigating the interactions between cover crops, soil moisture, and nutrient cycling in semi-arid regions like Kansas. Additionally, the development of precision agriculture tools to optimize phosphorus application based on site-specific conditions would be a valuable step toward more sustainable agricultural practices.