EFFECTS OF PHOSPHOROUS AND POTASSIUM APPLICATION TIMING ON A WHEAT DOUBLE-CROP SOYBEAN SYSTEM

By

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EFFECTS OF PHOSPHOROUS AND POTASSIUM APPLICATION TIMING ON A WHEAT DOUBLE-CROP SOYBEAN SYSTEM

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“For I know the plans I have for you,” declares the LORD, “plans to prosper you and not to harm you, plans to give you hope and a future. – Jeremiah 29:11

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Abstract: The wheat-double-crop soybean system is a popular choice for Oklahoma producers, as it allows for two crops in one year, and more revenue in less time. With favorable conditions and proper management, double-crop soybeans are yielding similar to full-season soybeans. While attempting to increase yield and profit of the summer crop, it is also important to not limit the potential of the winter wheat crop. This study is designed to evaluate the effects of phosphorus (P) and potassium (K) fertility management for a wheat-double-crop soybean cropping system, over three timings, to better understand how these affect the wheat and soybean yield. The study also determines if OSU fertilization rates based on soil tests are effective. This study consists of 13 treatments replicated 4 times that were established at planting of winter wheat. A total of 6 site-years spread out across Oklahoma over two years made up this research. The plots are 3.0 m x 6.0 m in size. Treatments include a flat N rate (27.2 kg N ha-1) over all plots at both pre-plant wheat and top-dress wheat. Treatments include four rates of P and K each. P and K rates based on OSU sufficiency soil test recommendations. N applied as 28-0-0, P applied as 0-46-0 (P2O5), and K applied as 0-0-60 (K2O). The plots were harvested with a Kincaid 8-XP plot combine unless hand harvested due to poor field conditions. Data collected included yield, test weight, protein, and oil content. Microsoft Excel and SAS 9.4 were used to run statistics for this trial. Oklahoma State University's winter wheat P and K recommendations based on the sufficiency approach maximized yields when P and K were the only limiting factors. As in previous work, locations with acidic soil pH responded to the addition of P fertilizer above sufficiency recommendations. At one location with low P and pH, in-season application of additional P at top dress maximized yield in wheat. Pre-plant application on soybeans has been found to significantly impact yield in one location, although further investigation of soybean data is needed.

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CHAPTER I

INTRODUCTION

Double-cropping soybeans (*Glycine max* L.) in Oklahoma is becoming a popular option for farmers looking to improve their profits in uncertain economic times. Double-cropping can be defined as harvesting two crops from the same field in one year (Borchers, et al., 2014). This system offers several advantages such as improving soil quality, reducing erosion, more efficient use of land and equipment, and providing more food and feed for an expanding world population (Holshouser, 2015). As double-crop soybean production increases, additional questions are being raised as to what the optimal fertilizer program for a wheat (*Triticum aestivum* L.) and soybean system is. Currently, published literature is lacking on the nutrient management practices for such a system. Currently, if producers add additional nutrients for the double-crop, above that which is needed for the winter wheat, it is applied as a single pre-plant application prior to the wheat crop. The need for additional nutrients above that of the primary cash crop; winter wheat, has not been documented much less the impact of the timing of nutrient application for the double-crop soybean. Therefore, this study will observe the impact of phosphorus (P) and potassium (K) fertilization rates and timings on a wheat-soybean double-crop soybean system.

CHAPTER II

REVIEW OF LITERATURE

Background

Double-cropping offers farmers a way to produce more food and fuel on less land for a growing population (Borchers, et al., 2014). If managed correctly, this practice also offers the possibility of greater net returns per acre. Approximately two percent of the farmland in the United States is double-cropped, approximately 2.4 to 4.4 million hectares; with soybeans accounting for 53% of that amount. First cultivated in China over 6,000 years ago, only in the 19th century did soybeans become a popular crop to grow in the United States (Imas and Magen, 2007). Soybean acres in the United States were also relatively low until after World War II. Today, soybeans are the world's most grown oilseed. Average oil concentrations of soybean are noted at 18-20% while protein concentration averages 38%. The wheat-soybean double-crop system is somewhat new compared to many cropping systems. Early attempts of double-cropping soybeans into wheat consistently failed, primarily due to the loss of moisture from cultivation (Coughenour, 2003). With the adoption of no-till management, the success of the wheat-double-crop soybean system increased. In an on-farm study performed in Oklahoma evaluating the response of a double-crop soybean to additional rates of nitrogen (N), P, K, or sulfur (S) by Reed and Arnall (2021) found that the addition of these nutrients increased yield in 23% of the 61 fields evaluated. Of the positive responses, P and K attributed to 15 of the 20 occurrences. The work by Reed and Arnall (2021) suggested the need for further work evaluating P and K management in a wheat soybean double-crop system.

Phosphorus

Phosphorus (P), is an essential plant nutrient that makes up between 0.05 and 0.50% of dry plant weight (Vance, et al, 2002). Phosphorous is a common limiting nutrient for crop yield on over 30% of the arable land in the world (Vance, et al, 2002). At the molecular level, P is a major element of adenosine triphosphate, nucleic acids, and phospholipids (Schachtman, et al., 1998). Important plant processes such as cell division, flowering and fruiting, seed production, and root development are not able to be performed properly without a sufficient supply of plant-available P (Brady, 1984). Plants require P for the dinitrogen fixation process and to stimulate whole-plant growth in general. Photosynthetic and dinitrogen fixation are both negatively affected if there is a deficiency or oversupply of P (Nuruzzaman, et al., 2005).

The major challenge when managing P in the soil is that the vast majority of P, more than 80%, is immobile and not available for plant uptake (Schachtman, et al., 1998). Most cropped soils have accumulated P over time due to large amounts of fertilizer applied over many years, but only approximately 15% of P applied is taken up by the crop during the year of application (Tsvetkova and Georgiev, 2003). Total soil P is classified into three pools: non-labile P (80 – 90% of the total P), labile P (< 10% of the total P), and solution P (< 1% of the total P) (Penn and Camberato, 2019). As mentioned above, most total soil P is non-labile P or unavailable. This is due to P being bound in compounds with aluminum (Al) and iron (Fe) in acidic soils and with calcium (Ca) and magnesium (Mg) in more alkaline pH soils (Penn and Camberato, 2019). Non-labile P is found in both organic and non-organic forms however is not biologically available. The release of phosphorus via weathering, mineralization, and dissolution from the non-labile P pool into labile and plant available forms is too slower than that of crop demand (Hansen, et al, 2002). Liable P or relatively available is the second largest P pool in the soil. The labile P pool can become plant available over a relatively short period of time but must first be released into solution before a plant can uptake it (Penn and Camberato, 2019). Labile P is found in both freshly decomposed organic forms and on soil exchange sites in an inorganic form. Labile P can refill the solution P pool as plant uptake or other loss reduce solution levels through mineralization, desorption, and dissolution (Hansen, et al, 2002). Solution P or readily available, is available for the crop at any given time, although it is by far the smallest pool of the three (Penn and Camberato, 2019) (Raun, et al, 2017). Solution P is the most reactive form of soil P and is made up of primarily orthophosphate anions such as $H_2PO_4^-$ and HPO_4^{2-} (Hansen, et al, 2002).

Several factors impact the availability of P in the soil, including soil pH, which is considered the major variable when considering the disposal of P. Maximum P availability occurs at a slightly acidic pH of 6.5, within a range of 5.5 to 7.2. Another range of availability is found at a much more acidic pH of 4.5, although most crops do not perform well at this acidity level. At the more acidic pH of 4.5, Fe and Al are at their lowest P fixation together, abet slightly higher than the first (Penn and Camberato, 2019).

Soil particle surface area also contributes to the availability of soil P to crops. Portions of P is adsorbed to the surface of clay particles, including Fe and Al hydrous oxides and even organic matter complexes. Even with large amounts of total P in most soils, it rarely leaches and is rarely plant-available due to chemical tie-up (Holford, 1997). The ease of replenishment of P into solution for the crop depends on the total amount of P in the soil and the P sorption or buffering capacity of that soil. The relationship is inverse in nature as the higher the buffering capacity, the slower any P comes into solution and vice versa. Sorptivity is measured through sorption isotherms; these define the quantity and intensity of sorption by soils. Not only buffering capacity but also the concentration of solid phase P must be considered to better understand the replenishment of P into solution of a certain soil (Holford, 1997).

Soil P availability is also impacted by microbial activity breaking down soil organic matter. Decomposition of organic matter by a microbial population immobilizes P in microbial tissue. In time the microbial tissue is mineralized and becomes available as solution P (Raun, et al, 2017).

Due to the complex soil P fixation processes, P fertilizer must often be added to a crop to ensure that the crop is not P deficient. Common fertilizer sources include ammonium phosphates such as $NH_4H_2PO_4$ (MAP 11-52-0), $(NH_4)_2HPO_4$ (DAP 18-46-0), and monocalcium phosphate $Ca(H^2PO_4)_2$ (TSP 0-46-0). Phosphorous fertilizer is not efficient, as studies have shown a range of applied first-year crop availability from 15 percent (Tsvetkova and Georgiev, 2003) to less than 30 percent. (Raun, et al, 2017). Knowing this, more fertilizer must be applied than what is needed for the crop

Potassium

Potassium (K) is a macronutrient required by plants to function properly (Brady, 1984). Like P, K is immobile in the soil, although not to the magnitude of P (Farhad, et al., 2010). Potassium is the most abundant mineral found in a plant, comprising up to 10% of a plant's dry matter weight. High concentrations of K can be found in growing tissues and reproductive organs, thus indicating that K is important in cell metabolism and growth. Potassium is important for the activation of enzymes in the rapidly expanding cells, as well as a counter for anion accumulation (White and Karley, 2010). Potassium plays a role in determining plant height, grain yield, biomass yield, and protein levels. Factors such as oil content do not seem to be significantly affected by K (Farhad, et al., 2010). Potassium is taken up rapidly during the vegetative growth of soybeans and slows during the reproductive phase (Imas and Magen, 2007). Potassium also affects the drought resistance of plants. During periods of dry weather, root growth and the uptake of K is limited, therefore applied K fertilizer will mitigate these restrictions, helping with root growth, growth rate, and water use efficiency (Reed, 2021)).

Potassium chemistry is less complex when compared to P as it exists as K^+ typically in the soil and rarely forms covalent bonds (Syers, 1998). This prevents most, if not all organic combinations from forming. Potassium is classified into four forms occluded K (98% total soil K), fixed K (1% total soil K), exchangeable K (1% total soil K), and solution K (0.01% total soil K) (Raun, et al, 2017). The majority of soil K is found in crystalline forms as feldspars and mica minerals and therefore is unavailable. Over time, these minerals will weather and release K into fixed K, exchangeable K, and solution K forms. Fixed K is believed to be trapped on adsorption sites between layers of micaceous clay minerals. These sites are created when the micaceous clay particles, or illites, weather down and expand or when vermiculite clay interlayers are developed (Syers, 1998). Only a small percentage of fixed K will be used by crops at any given time as K is released and cycled between different forms during the growing season. Exchangeable K is the third form of soil K found attached to negatively charged cation-exchange sites such as organic matter and clay minerals. This form is in rapid equilibrium with the more available solution K. Studies have shown that a correlation exists between exchangeable K and crop yield (Syers, 1998). The last form of soil K is known as solution K, it is found in the soil water and on clay particle exchange sites. When testing for K using soil tests, the results are in this form. This form of soil is most available for plant use. Plants absorb soil water and thus take up K at the same time. As more K is drawn into the plant, more K is released from the exchange sites and placed into the soil water (Prajapati and Modi, 2012).

As crops take up K in solution, portions of K held between clay layers will diffuse into the solution to have a steady supply of K for crops (Pettygrove et al., 2011). Montmorillonite-type clays found in central and western Minnesota fix K between clay layers during dry periods and release K during wet periods. Illite clays also fix K during dry periods, however, do not release all fixed K during wet periods (Prajapati and Modi, 2012). Results from a study in Pakistan indicate that fixation increased as the amount of clay in soil increased, along with increased application rates of K. Another finding indicated that as the amount of K applied increased, the percentage of K applied that was fixed decreased (Ranjha, et al., 1990). The availability of K in any certain soil depends on many factors including soil texture, clay type, pH, cation exchange capacity (CEC), and climate. Clay dominant soils store more K compared to loam and sandy type soils, and as a result, clay soils leach less compared to sandy soils. For two soils with similar total K, the high CEC soil will store more K, leach less K, and have less K in the solution (Rosolem, et al., 2010).

Potassium chloride (KCl), also known as potash (0-0-60), is the primary K fertilizer used throughout the world (Prakash and Verma, 2016). The application type and timing of K fertilizer should be adjusted to best fit the CEC of the soil. Lower CEC soils of less than 15 meq/100 g of soil should receive smaller rates of K more frequently to continually replenish past K reserves that have leached or been taken up by plants. These soils cannot store or fix as much K as other higher CEC soils. Soils with a CEC of 15 to 30 or higher can receive higher rates of K fertilizer less frequently. Banding of K is a favorable option, especially in the higher part of this range. Soils in this range can store and fix more K; therefore, application frequency can be reduced. It is important to apply enough K to maintain the fixation-release balance. Along with soil texture and CEC, the influence of climate on the availability of K should be considered. Dry conditions often limit the availability of K in the top layer of the soil, while an excessive amount of moisture will leach K deep into the soil, the amount depending on soil texture (Bell, et al., 2017).

Nutrient Stratification

Approximately 45 % of wheat and 40 % of soybeans are no-tilled in the United States (Claassen, et al., 2018) with the remainder of the wheat and soybeans either under mulch till or conventional till. Double-cropping in Oklahoma is primarily utilized in conjunction with no-tillage practices. Moisture is often the limiting factor for Oklahoma producers, so it is often necessary to no-till double-crops to have adequate moisture for crop emergence.

The type of tillage system used in conjunction with fertilizer applications and moisture conditions can impact nutrient availability to the crop. Conventional tillage practices mix the top 15 to 20 cm of soil, along with mixing in any P and K fertilizer applied. No-tillage practices on the contrary do not disturb the soil, and the fertilizer is concentrated in the top 5 cm of soil, with over three times greater P and K concentrations compared to 5 to 15 cm deep in the soil profile (Bigatoa Souza and Arnall 2021). This stratification of P and K in the top layer of the soil does not impact crop availability if adequate moisture is in the top layer of soil so that the crop roots can proliferate through the top layer. No-till is reported to increase moisture retention in the soil, so this is usually not an issue. However, under continuous drought conditions, nutrient stratification can become an issue due to the drying of the top layers of soil first (Robbins and Voss, 1991). Drought conditions are more prolific during the summer growing season when double-crops are planted, therefore nutrient stratification is a concern.

Wheat Growth Stages and Nutrient Uptake

Feekes 1.0 is the emergence and the formation of the shoot (Miller, et al., 1992). The second stage, Feekes 2.0 is the beginning of tillering, where a shoot forms out of the axil of a leaf or from the coleoptilar node. At this stage, producers should decide if the stand is uniform and consistent, as poor stands will rarely meet yield goals even with added inputs. At Feekes 3.0 tillers are considered formed (Miller, et al., 1992). Depending on weather conditions and planting date, tillering may be completed before winter dormancy or continue into the spring. Tillers that contribute to grain yield are almost exclusively formed in this period. Feekes 4.0 is the period of erect growth and the lengthening of leaf sheaths. At this stage, the secondary root system is developing, and the last tillers are forming. Total nutrient uptake reaches 20 % at the beginning of Feekes 5 (De Oliveira Silva, et al., 2021). Once a wheat crop reaches Feekes 5.0, leaf sheaths become strongly erect, and tillering ceases at this stage (Miller, et al., 1992).

Vernalization is required before any more growth and development will occur. As temperatures increase in the spring, the growing point differentiates; all leaves are formed, and the spike head will begin to develop. During Feekes 5.0, the number of spikelets per spike is determined. Feekes 6.0 is easier to identify compared to other stages because the true stem is beginning to form (Miller, et al., 1992). The first node swells and is above the soil surface. The spike is above the first node and is now differentiated, thus containing all spikelets and florets, the seed forming branches. Once the second node is visible above ground, the wheat has reached Feekes 7.0. At this stage, the second to last leaf becomes visible, and the spike or head goes through a rapid expansion and growth. The period of Feekes 8.0 begins once the flag leaf begins to come out of the whorl, and eventually makes up approximately 75 % of the leaf area that contributes to grain fill. At this stage, 50 % of total nutrient uptake has occurred (De Oliveira Silva, et al., 2021). At Feekes 9.0 the ligule of the flag leaf is visible and other leaves are named in relation to the flag leaf (Miller, et al., 1992). Total nutrient uptake at Feekes 9.0 has reached 70 % (De Oliveira Silva, et al., 2021), and once Feekes 10.0 begins, maximum P and K uptake is occurring (Malhi, et al., 2006). Also known as the boot stage, the head emerges from the leaf sheath, and flowers, and begins to ripen (Miller, et al., 1992).

The various stages of heading and flowering are broken down into several sub-growth stages in Feekes 10.0. The final growth stage is the ripening stage, also known as Feekes 11.0. Like Feekes 10.0, Feekes 11.0 is separated into four stages of the ripening process. They are as follows: 11.1 milky ripe, 11.2 mealy ripe, 11.3 kernels hard, and 11.4 harvest-ready. Grain fill lasts between as few as 30 days and more than 50 days depending on stress level and environmental conditions.

Figures 1 and 2 adapted from (De Oliveira Silva, et al., 2021), further represent P and K uptake at different Zadoks growth stages (Figure 1) and provide maximum P and K (kg ha^{-1}) uptake in winter wheat at physiological maturity.

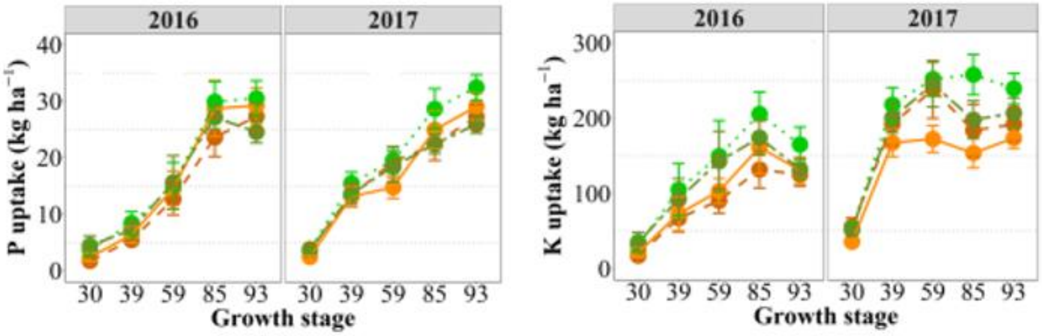


Figure 1. Adapted from (De Oliveira Silva, et al., 2021), nutrient uptake of phosphorous and potassium at different growth stages at two winter wheat trials conducted in Manhattan and Belleville, KS. Growth stage is in Zadoks scale: 30 = early stem elongation, 39 = flag leaf emergence, 59 = anthesis, 85 = soft dough, 93 = physiological maturity.

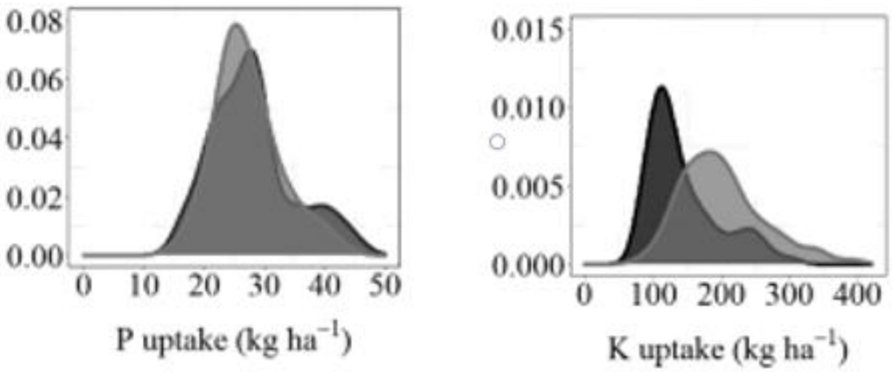


Figure 2. Adapted from (De Oliveira Silva, et al., 2021), distribution of observations for phosphorous and potassium uptake at physiological maturity (kg ha^{-1}) for two winter wheat trials conducted in Manhattan and Belleville, KS. The highest concentrations of data points are represented by the peak of each curve.

Soybean Growth Stages and Nutrient Uptake

Soybean growth and development are followed through the use of growth staging similar to wheat. A better understanding of the growth stages can improve management decisions and maximize yields and profits. Soybean varieties are described in three categories; indeterminate, semi-determinate, and determinate (McWilliams, et al., 1999). Determinate varieties are grown in the southern United States, where vegetative growth stops when the main stem terminates into a cluster of pods, while indeterminate varieties are primarily grown in the northern United States and continue to develop leaves and flowers concurrently through the reproduction period. Only the changing of the seasons limits vegetative growth in indeterminate varieties. Semi-determinate soybeans are often found in the mid-west and between regions of determinate and indeterminate varieties.

Soybean varieties are split into different maturity groups, running east to west with, approximately 100-150 miles in each belt north to south (McWilliams, et al., 1999). Day length and warm temperatures control when soybeans begin flowering. For flowering to occur the first trifoliolate must be reached. Generally, soybeans in the northern United States require longer day lengths than soybeans in the south to flower. Annual differences in flowering time do occur, even between the same varieties.

The growth stages of soybeans are separated into vegetative and reproductive stages (McWilliams, et al., 1999). The vegetative stages are emergence (VE), cotyledon stage (VC), first trifoliolate (V1), second trifoliolate (V2), and third trifoliolate (V3), fourth trifoliolate (V4), fifth trifoliolate (V5), and flowering will soon start (V6). After the cotyledon stage (VC), the vegetative stages are numbered by the number of completely developed nodes on the main stem but exclude branches that are not off the main stem. The reproductive stages are as follows: beginning bloom, (R1), full bloom, (R2), beginning pod (R3), full pod (R4), beginning seed (R5), full seed (R6), beginning maturity, (R7), full maturity (R8).

Emergence (VE) takes five to ten days depending on planting depth, moisture conditions, temperature, and variety planted (McWilliams, et al., 1999). Germination of soybean seed begins when the seed has absorbed approximately 50% of the seed’s weight. The radicle or primary root is the first to extend out of the root. After the radicle, the hypocotyl or stem begins the climb out of the seed and up towards the surface. Epicotyl growth begins pulling up and unfolding the unifoliate leaves. The cotyledon stage (VC) starts with the unifoliolate leaves being completely expanded. During this first week to 10 days, the cotyledons are providing nutrients for growth, and therefore, losing 70% of dry weight. Plants can lose one cotyledon and be minimally affected. The first trifoliolate (V1) stage is complete once the first trifoliolate has emerged and completely opened. Soybeans reach the second trifoliate once the plant is 6-8’’ tall and has two completely unfolded leaves. During the third to fifth trifoliolate (V3-V5), the soybean plant continues to grow taller and produce more nodes. At (V3) the plant is 7-9’’ tall and by (V5) the plant has reached 10-12’’ tall. Once (V5) is reached, axillary buds have developed at the top of the main stem and will eventually flower. Approximately one week after V5, flowering will begin. A soybean plant will be 12-14’’ tall at sixth trifoliolate (V6). At this stage, there are seven nodes with leaves unfolded. Although the plant is preparing to go into the reproductive stages, the plant can still recover from damage and have little loss of yield.

The reproductive stages begin with beginning bloom (R1), where there is at least one flower somewhere between the third and sixth node on the main stem (McWilliams, et al., 1999). Flowering always begins in this area and will spread up and down the main stem, along with the branches. The plant will be 15-18’’ tall and at (V7-V9) in vegetative terms. At full bloom (R2), at least one of the two top nodes on the main stem will have a fully developed leaf and have one an open flower in the same place. The plant has reached approximately 25% of its total dry weight and at 17-22” tall it has reached 50% of its mature height (McWilliams, et al., 1999). Nutrient uptake of P and K by the plant increases rapidly during this stage and continues this pace for a few following stages. Only 25% of nutrients have been taken up at this point. Soybean plants reach 23-32” tall and (V8-V12) in vegetative growth. A pod begins to form on the upper four nodes. As the plant matures, temperature or moisture stress will have a bigger impact on the final yield. Total pod number, bean number per pod, and seed size are all affected by stresses at this stage. Stress will also cause soybean plants to abort 60-75% of flowers, thus reducing potential yield. Flowers are lost before pods begin to form and because of pod abortion, however, plants can make up for the loss through their long flowering period. Rapid pod growth and the start of seed development are features of the full pod (R4) stage. There will be a pod at least ¾” long on one of the top four nodes. Stress during this period can be extremely detrimental to yield, as this is the most important stage for seed development. Yield reduction will primarily be in the loss of pods. Flowering is still occurring and will continue into the next stage. Beginning seed (R5) requires large amounts of water and nutrients due to seed filling. Nutrient redistribution from the plant’s vegetative parts provides approximately 50% of needed P and K; nutrient uptake through the roots provides the rest needed. As similar in the last stages, stress can reduce yield through the loss of pods, reduction of seeds per pod, and to some extent seed size. The plant will reach its maximum height, leaf area, and node number during this stage.

The full seed (R6) or “green bean” stage begins when a pod containing a green seed that fills the pod cavity. Bean growth at the beginning of (R6) is fast, as total pod weight will peak, although this rate slows after (R6.5). Root growth is finishing, and three to six leaves will fall from the bottom of the plants. The beginning maturity (R7) stage begins when one pod on the main stem turns brown. At this point seed dry weight increases and eventually peaks, while seed moisture is reduced to 60%. Neither stress nor a killing frost will cause any meaningful damage to potential yield. Once 95% of the pods have turned brown and reached maturity the final stage of full maturity (R8) begins. Soybeans will begin to dry down rapidly, and as few as 5 to 10 days is required to lower the moisture enough to begin harvest.

A soybean nutrient uptake study found that the maximum total accumulation of P was reached at R6.5, while maximum K accumulation was completed slightly earlier at

R6 (Bender et al., 2015). Total P and K uptake through the growing season was 21 and 142 kg ha^{-1} respectively, while the amount of P removed by the grain averaged 17 kg ha^{-1} and the amount of K removed averaged 64 kg ha^{-1}. Harvested grain removed 80 % of total P taken up by the soybean plant compared to only 45 % of total K. Figure three represents where both P and K are stored in the plant, as well as how these stores change in the plant as the growing season progresses. Grain rain uses the majority of P while the stems and petioles store much of the K for most of the growing season.

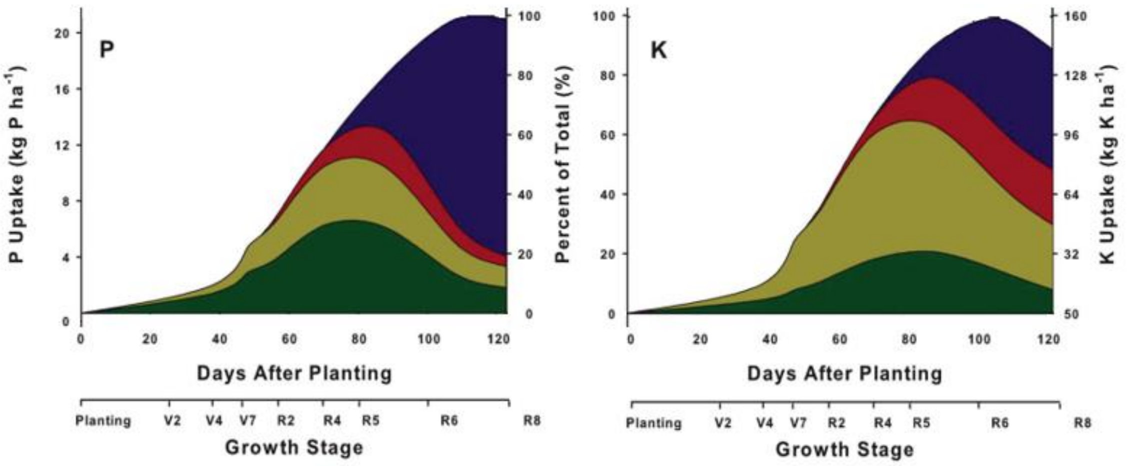


Figure 3. Adapted from (Bender, et al., 2015), nutrient uptake curve for phosphorous and potassium during the soybean cycle. Amount of uptake represented in (kg ha-1) and percent (%) of total uptake between grain (blue), flowers and pods (red), stems and petioles (yellow), and leaves (green). on the Y-axis. Days after planting and growth are represented on the X-axis.

Agronomic Practices

Winter wheat is well suited for Oklahoma’s cool and wet fall and spring seasons, along with the hot summers and cold, dry winters. Wheat is planted between early September and mid-November and harvested between late May and mid-July. Wheat planted for dual-purpose grazing may be planted earlier and wheat planted for grain only is planted in the latter part of the time allotted. When planting, wheat should be seeded to a depth of 1.3 cm to 3.8 cm depending on the moisture content in the soil (County, et al.). To avoid winter damage, wheat stands need time to establish crown roots and three to five tillers. Planting near the Hessian fly-free date will ensure enough time for adequate growth before winter. The seeding rate varies widely from 1,483,000 to 3,336,000 seeds ha^{-1} depending on environmental factors and mechanical factors (Paulsen, et al., 1997). For drilled wheat, row spacing commonly ranges from 15 cm to 25 cm.

Soybeans will grow in a wide range of soils and climates if managed correctly for that area. Ideal soils for soybean production are loamy, deep, well-drained soils. Lighter, sandy soils will still produce a good crop in many cases; however, they do not have the water or nutrient holding capacity needed for optimum soybean production. Soybeans can be planted in Oklahoma from April to early July. Many considerations should be made while deciding when to plant. Soybeans are photosensitive, meaning that flowering is determined by the length of light and dark periods of a day. Growing degree days have little impact on flowering in soybeans, unlike corn. Warm temperatures during the vegetative stage of the crop results in large plants and earlier flowering.

For soybean germination, to occur soil temperatures must be at least 55 degrees F. For best germination, soil temperatures should range from 68 to 86 degrees F. Heavy-textured soils will take more time to warm up to adequate germination temperatures than lighter, sandy soils. Moisture is critical for germination, as the seed must absorb 50% of its weight to begin the germination process. Soybean seedlings can tolerate the cool weather of early spring; however, they do not tolerate cool and wet weather (Arnall et al., 2020). When evaluating row spacing’s impact on dry matter accumulation in soybeans, accumulation at R1, R5, and R7 was greater for plants in 18 cm rows than those plants in 54 cm rows (Coale and Grove, 1990). The only part that was opposite was the branches. The increased dry matter on narrow rows was attributed to row width and plant population difference. Wider rows could not maintain plant population as well as the narrow rows, which was attributed to intra-row competition in the wider rows. Soil temperature could potentially affect plant emergence and harvest density more than soil moisture up until mid-June. Soybean grain yield is determined more by harvested plant population than seeding rates Differences in harvested plant populations accounted for 61% of the variation in yield and only 39% of yield variation was from tillage practices and seeding rates.

Soybean practices used in conventional till also work for reduced till no-till. Such practices include early planting, narrow rows, and the selection of high-yielding cultivars (Oplinger and Philbrook, 1992). A 32% increase in seeding rate over conventional-till can produce equal yields when using ridge-till or no-till. Full season soybean yields exceeded double-crop yields because of more pods per plant and larger seeds. The planting date did not affect the number of seeds per pod (Coale and Grove, 1990). Marginal yield compensation can be achieved through improved stands at a later planting date however, this will not make up for the shorter growing season (Oplinger and Philbrook, 1992).

CHAPTER III

OBJECTIVE

The objective of this study was to evaluate the impact of P and K application rate and timing on a wheat double-crop soybean system. There is a need to better understand how to maximize double-crop soybean yields without negatively impacting the winter wheat yields. The first and primary objective is to determine if the soybean crop benefits from rates of P and K applied beyond that of the winter wheat recommendation. If a positive impact of the additional P or K is found, then additional objectives will be important. As the additional fertilizer can be applied as a pre-plant application in wheat, as a top-dress application in wheat, or as a pre-plant application in the soybean cycle. It is important to understand the impact of this timing on both crops within the system.

CHAPTER IV

METHODOLOGY

This study consisted of six site years with trials at the Eastern Research Station (ERS) near Haskell, Oklahoma, Ballagh Family Research Farm (BFRF) near Newkirk, Oklahoma, Skagg Family Farm (SFF) near Lamont, Oklahoma, and Lake Carl Blackwell Research Farm (LCBRF) near Perry, Oklahoma. The research was conducted during the 2019-2020 growing season and the 2020-2021 growing season. Two locations were established during the first season and four during the second season (Table 1). The variety of locations and two growing seasons provided a range of environments across Oklahoma.

Table 1. Location name, county, and latitude and longitude of the six sites where the phosphorous and potassium wheat double-crop soybean trials were established over the two growing seasons of 2019-2020 and 2020-2021.

Year	**Location**	**County**	**Latitude**	**Longitude**
2019-2020	ERS	Muskogee	35.742425	-95.6354
2019-2020	BFRF	Kay	36.795872	-96.9976
2020-2021	ERS	Muskogee	35.744944	-95.6416
2020-2021	SFFN	Grant	36.693839	-97.5346
2020-2021	SFFS	Grant	36.685339	-97.5355
2020-2021	LCBRF	Payne	36.151703	-97.2898

Table 2. Soil series name and taxonomic class of the six sites where the phosphorous and potassium wheat double-crop soybean trials were established over the two growing seasons of 2019-2020 and 2020-2021.

Year	Location	Taxonomic Class
2019-2020	ERS	Taloka Silt Loam (Fine, mixed, active, thermic, Mollic Albaqualfs)
2019-2020	BFRF	Foraker-Pawhuska Complex (Fine, smectitic, thermic Udertic Argiustolls) (Fine, mixed, superactive, thermic Mollic Natrustalfs) Agra-Foraker Complex (Fine, mixed, superactive, thermic Udertic Paleustolls) (Fine, smectitic, thermic Udertic Argiustolls)
2020-2021	ERS	Taloka Silt Loam (Fine, mixed, active, thermic Mollic Albaqualfs) Parsons Silt Loam (Fine, mixed, active, thermic Mollic Albaqualfs)
2020-2021	SFFN	Lovedale Fine Sandy Loam (Fine-loamy, mixed, superactive, thermic Udic Argiustolls)
2020-2021	SFFS	Lovedale Fine Sandy Loam (Fine-loamy, mixed, superactive, thermic Udic Argiustolls) Renfrow Silty Clay Loam (Fine, mixed, superactive, thermic Udertic Paleustolls)
2020-2021	LCBRF	Pulaski Fine Sandy Loam (Coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvents)

The trials consisted of thirteen treatments replicated four times arranged in a randomized complete block design (RCBD). Plot size was 3 m x 6.1 m with 3 m alleys between the replications. Phosphorous and K fertilizer were applied at three timings. Treatment applications were made at wheat pre-plant, wheat top-dress, or at the planting of the double-crop soybeans (Table 3). Treatments consisted of combinations or single applications of P and K. Multiple P and K treatments were determined using Oklahoma

State University (OSU) recommendations based on pre-plant soil tests. Current OSU soil sufficiency recommendations are 32.5 ppm of P and 125 ppm of K for winter wheat production and 32.5 ppm of P and 137.5 ppm of K (Zhang, et al, 2017).

Table 3. Treatment structure for the phosphorous and potassium application in a winter wheat double-crop soybean system study. Applied rates based on OSU soil sufficiency recommendations were used in each location. Rates are represented under Pre-wheat, Top-dress, and Pre-DC Soybeans. Treatments with a "+" next to the letter within the preplant wheat timing represent the addition of the recommended OSU fertilizer recommendation for P and K for soybeans based on the oil test.

Treatment	**Label**	**Preplant Wheat**	**Top-dress Wheat**	**Preplant Soybeans**
1	N Only	N	N	
2	P	NP	N	
3	K	NK	N	
4	PK	NPK	N	
5	P+K	NP+K	N	
6	PK+	NPK+	N	
7	P+K+	NP+K+	N	
8	TD-P	NPK	NP	
9	TD-K	NPK	NK	
10	TD-PK	NPK	NPK	
11	S-P	NPK	N	P
12	S-K	NPK	N	K
13	S-PK	NPK	N	PK

Pre-plant wheat soil samples were taken at a 0-15 cm depth with 2.54 cm diameter soil probes at each trial (Table 4). The samples were dried and ground to pass through a 2 mm sieve. The samples were then analyzed for pH and buffer index using a 1:1 soil: water suspension and glass electrode (Sims, 1996; Sikora, 2006). The samples were analyzed for P and K concentration using Mehlich-3 extractant solution (Mehlich, 1984) and analyzed using an ICP spectrometer (Soltanpour, et al., 1996).

Table 4. Composite 0-15 cm pre-plant soil sample results from each location for soil pH, organic matter (OM) from the Mehlich 3 phosphorous (M3P), and potassium (K) in the winter wheat double-crop soybean system study.

Year	**Location**	**pH**	**OM (%)**	**M3P (ppm)**	**K (ppm)**
2019-2020	ERS	5.6	1.68	19.5	37.5
2019-2020	BFRF	7.0	na	19.0	102.5
2020-2021	ERS	5.7	1.20	10.0	31.0
2020-2021	SFFN	6.2	1.24	20.5	97.0
2020-2021	SFFS	5.4	0.67	9.0	70.5
2020-2021	LCBRF	6.0	na	11.5	99.0

Phosphorous and K fertilizer were applied by hand in granular form. Phosphorus was applied as triple superphosphate (0-46-0) and K was applied as muriate of potash (0-0-60). A flat rate of 67.25 kg N ha^{-1} as urea ammonium-nitrate (UAN) was applied on all plots at all trial locations at pre-plant and top-dress wheat timing.

The two trials at the ERS location were planted with a John Deere 1560 no-till drill set at 19 cm for wheat and 38.1 cm for soybeans. The BFRF trial was planted with a John Deere no-till air drill planting at 19 cm for both the wheat and soybeans. The LCBRF trial was planted with a Great Plains 1006NT no-till drill at 19 cm for wheat and 38.1 cm for soybeans. The wheat at the SFF trials was planted with a Landoll drill set at 19 cm and soybeans were planted with a Kinze planter set at 38.1 cm spacing.

Seeding rates for the ERS 2019-2020 trial were 89.7 kg ha^{-1} (wheat) and 357,000 seeds ha^{-1} (double-crop soybeans). Seeding rates for the BFRF trial were 123.3 kg ha^{-1} (wheat) and 312,000 seeds ha^{-1} (double-crop soybeans). Seeding rates for ERS 2020-2021 trial and LCBRF trial were both 89.7 kg ha^{-1}. Table 5 has all planting dates and cultivar information for the study.

Table 5. Location name, wheat planting date, wheat variety, soybean planting date, and soybean variety of the six sites where the phosphorus and potassium application in a wheat double-crop soybean trials were established over the two growing seasons of 2019-2020 and 2020-2021.

Year	Location	Wheat Planting Date	Wheat Variety	Soybean Planting Date	Soybean Variety
2019-2020	ERS	11-1-19	OGI Bentley	6-25-20	Armor 48-D25
2019-2020	BFRF	10-18-19	OGI Bentley	6-27-20	Asgrow 48x7
2020-2021	ERS	10-16-20	OGI Smiths Gold	7-8-21	Armor 48-D25
2020-2021	SFFN	10-4-20	LCS Fusion	6-25-21	Dynagro S46xS60
2020-2021	SFFS	10-4-20	LCS Fusion	6-25-21	Dynagro S46xS60
2020-2021	LCBRF	10-20-20	OGI Smiths Gold	7-9-21	Armor 48-D25

The LCBRF trial soybeans were irrigated intermittently when conditions were dry using an overhead linear irrigation system. Irrigation was applied three times during the 2021 soybean growing season.

Table 6. Irrigation date and amount (cm) at the Lake Carl Blackwell 2019-2020 location. Only the soybeans were irrigated.

Irrigation Date	Irrigation Amount (cm)
July 27, 2021	1.905
October 4, 2021	1.905
October 8, 2021	1.905

At maturity, the BFRF, LCBRF, SFFN, and SFFS wheat and the ERS 2019-2020, BFRF, and LCBRF soybean trials were harvested by a Kincaid 8-XP plot combine (Kincaid Equipment Manufacturing; Haven, KS). Yield data was collected by a Harvest

Master Grain-Gage onboard monitoring computer (Juniper Systems; Logan, UT), and grain samples were collected from each plot. The center 1.5 meters of each plot were harvested with the plot combine. The ERS 2020-2021 wheat and the ERS 2020-2021, SFFN, and SFFS soybean trials were harvested by hand due to poor field conditions. One-meter square sections were harvested out of each plot. Following hand harvest, samples were threshed and weighed to calculate yield. Combined and hand-harvested samples were analyzed by using near-infrared reflectance (NIR) to collect protein levels on wheat and soybeans, along with oil content on soybeans. Data analysis was conducted using PROC MIXED procedures (Tukey adjustment, alpha=0.05) in SAS software, version 9.4 (SAS Institute Inc., Cary, NC, USA).

CHAPTER V

RESULTS

Eastern Research Station (ERS) 2019-2020 Haskell, Oklahoma

Soil test M3P and K results for the ERS 2019-2020 were 19.5 and 37.5 ppm respectively. Soil test results indicate a 90 % P sufficiency and a 70 % K sufficiency for wheat and a 90 % P sufficiency and a 60 % K sufficiency for soybeans (Zhang, et al, 2017). Fertilizer P and K rates are provided in table 7.

Table 7. Fertilizer phosphorous and potassium application rates (kg ha^{-1}) of treatments for the ERS 2019-2020 trial.

Treatment	P	K	PK	P+K	PK+	P+K+	TD-P	TD-K	TD-PK	S-P	S-K	S-PK
P (kg ha^{-1})	9.8	0	9.8	19.6	9.8	19.6	19.6	9.8	19.6	19.6	9.8	19.6
K (kg ha^{-1})	0	46.3	46.3	46.3	111.2	111.2	46.3	111.2	111.2	46.3	111.2	111.2

Significant differences were observed for the 2020 soybeans for yield at (α) = 0.05. The average yield for the 2020 soybean trial was 2.6 Mg ha^{-1}. Potassium application above that of the wheat recommendation significantly increased soybean yields, applied at preplant wheat and preplant soybean. It should be noted that the top-dress application of K did increase yield however not statistically greater than that of the K treatment only receiving wheat K.

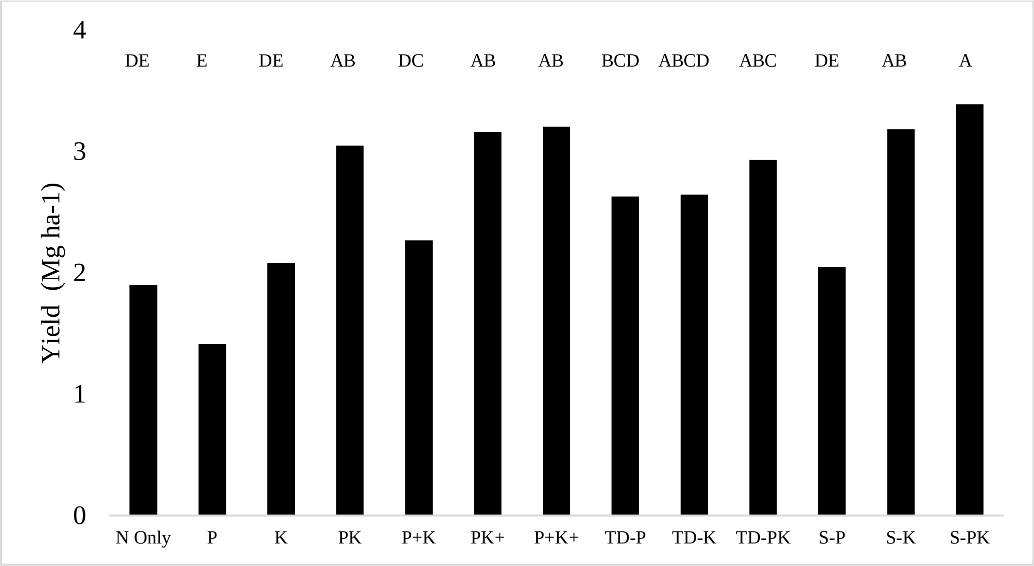


Figure 4. Grain yields, Mg ha^{-1}, from the soybean cycle of the 2019-2020 ERS trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

Ballagh Family Research Farm (BFRF) 2019-2020 Newkirk, Oklahoma

Soil test M3P and K results for the BFRF 2019-2020 were 19 and 102.5 ppm respectively. These soil test results indicate a 90 % P sufficiency and a 95 % K sufficiency for wheat and a 90 % P sufficiency and a 90 % K sufficiency for soybeans (Zhang, et al, 2017). Fertilizer P and K rates for each treatment are provided in Table 6.

Table 8. Fertilizer phosphorous (P) and potassium (K) application rates (kg ha^{-1}) of treatments for the BFRF 2019-2020 trial.

Treatment	P	K	PK	P+K	PK+	P+K+	TD-P	TD-K	TD-PK	S-P	S-K	S-PK
P **(kg ha^{-1})**	9.8	0	9.8	19.6	9.8	19.6	19.6	9.8	19.6	19.6	9.8	19.6
K **(kg ha^{-1})**	0	18.5	18.5	18.5	55.6	55.6	18.5	55.6	55.6	18.5	55.6	55.6

The average winter wheat grain yield at BFRF in the 2019-2020 location was 6.5 Mg ha^{-1}. Significant differences were observed at the BFRF in grain yield at (α) = 0.05. The N only yielded significantly less than all treatments except for P and TD-P. The treatments P+, PK+, P+K+, and TD-K were all significantly greater than the P treatment, which only received the P recommended for the wheat cycle. The application of K fertilizer, with exception of TD-P TD-PK, significantly increased yield above the N-only check. However, the K treatment, which was the rate of potash recommended for the wheat only, yielded equal to all other treatments receiving additional K for the soybean cycle. The average grain yield for the soybean cycle at this location was 1.9 Mg ha^{-1}.

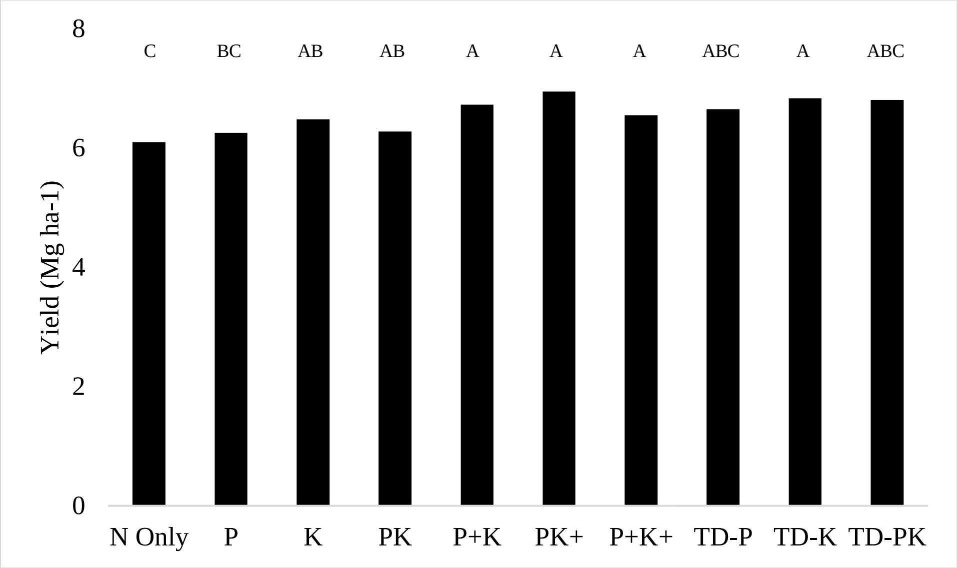


Figure 5. Grain yields, Mg ha^{-1}, from the winter wheat cycle of the 2019-2020 BFRF trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

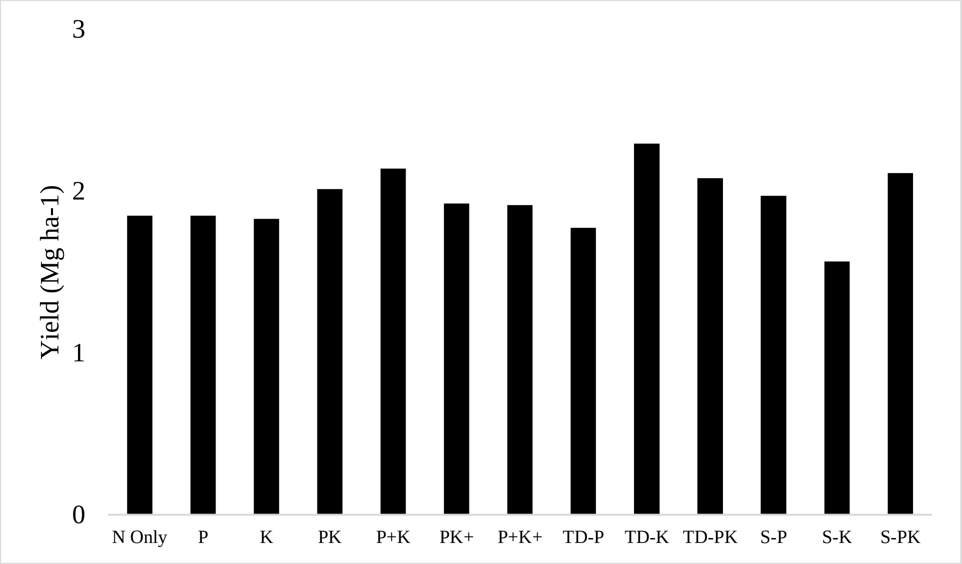


Figure 6. Grain yields, Mg ha^{-1}. from the soybean cycle of the 2019-2020 BFRF trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

Eastern Research Station (ERS) 2020-2021 Haskell, Oklahoma

Soil test M3P and K results for the ERS 2020-2021 were 10 and 31 ppm respectively. These soil test results indicate an 80 % P sufficiency and a 60 % K sufficiency for wheat and an 80 % P sufficiency and a 60 % K sufficiency for soybeans (Zhang, et al, 2017). Fertilizer P and K rates for each treatment are provided in table 8.

Table 9. Fertilizer phosphorous and potassium application rates (kg ha^{-1}) of treatments for the ERS 2020-2021 trial.

Treatment	P	K	PK	P+K	PK+	P+K+	TD-P	TD-K	TD-PK	S-P	S-K	S-PK
P (kg ha^{-1})	19.6	0	19.6	34.3	19.6	34.3	34.3	19.6	34.3	34.3	19.6	34.3
K (kg ha^{-1})	0	50.9	50.9	50.9	120.4	120.4	50.9	120.4	120.4	50.9	120.4	120.4

Yields at the ERS 2020-2021 were not significant at Alpha (α) = 0.05 for winter wheat or the following soybeans. The 2020-2021 average winter wheat and soybean yield was 1.6 Mg ha^{-1} and 2.6 Mg ha^{-1} respectively.

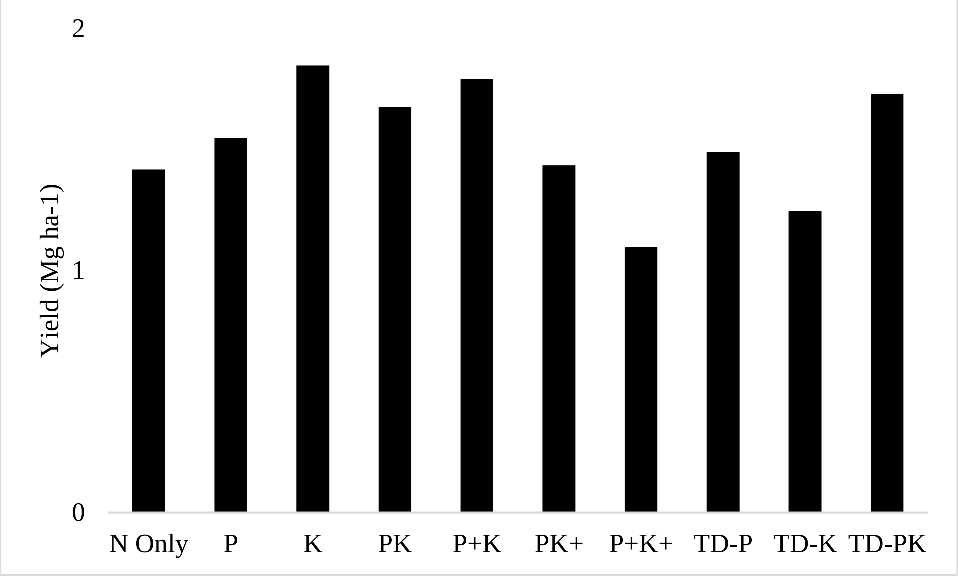


Figure 7. Grain yields, Mg ha^{-1}, from the winter wheat cycle of the 2020-2021 ERS trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

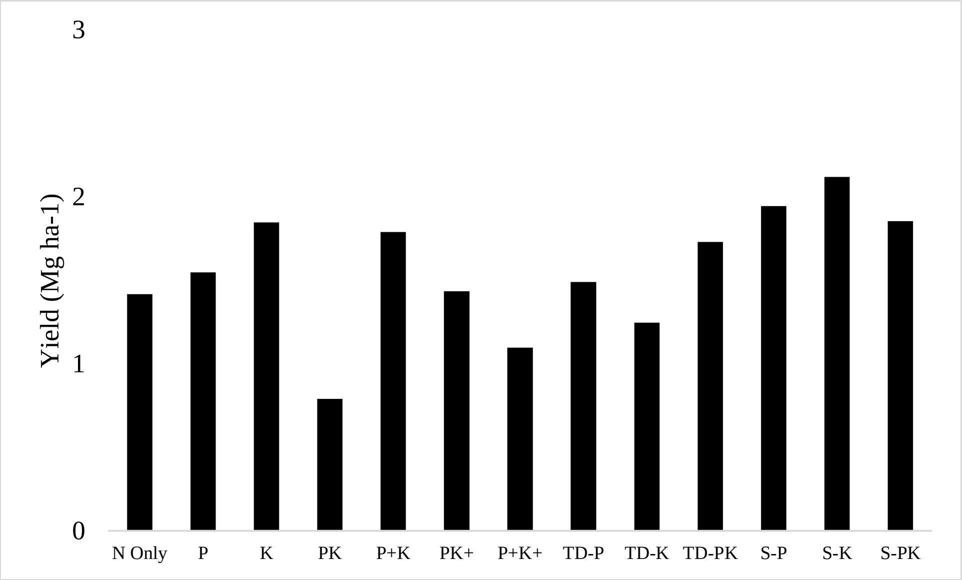


Figure 8. Grain yields, Mg ha^{-1}, from the soybean cycle of the 2020-2021 ERS trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

Skaggs Family Farm North (SFFN) Lamont, Oklahoma

Soil test M3P and K results for the SFFN 2020-2021 were 20.5 and 97 ppm respectively. These soil test results indicate a 95 % P sufficiency and a 95 % K sufficiency for wheat and a 90 % P sufficiency and a 90 % K sufficiency for soybeans (Zhang, et al, 2017). Fertilizer P and K rates for each treatment are provided in table 10.

Table 10. Fertilizer phosphorous and potassium application rates (kg ha^{-1}) of treatments for the SFFN 2020-2021 trial.

Treatment	P	K	PK	P+K	PK+	P+K+	TD-P	TD-K	TD-PK	S-P	S-K	S-PK
P **(kg ha^{-1})**	9.8	0	9.8	19.6	9.8	19.6	19.6	9.8	19.6	19.6	9.8	19.6
K **(kg ha^{-1})**	0	18.5	18.5	18.5	55.6	55.6	18.5	55.6	55.6	18.5	55.6	55.6

No significant grain yield difference was observed at (α) = 0.05. The average winter wheat grain yield was 3.7 Mg ha^{-1}. For the following soybeans, no significant yield difference was observed at (α) = 0.05. The average soybean yield was 1.2 Mg ha^{-1}.

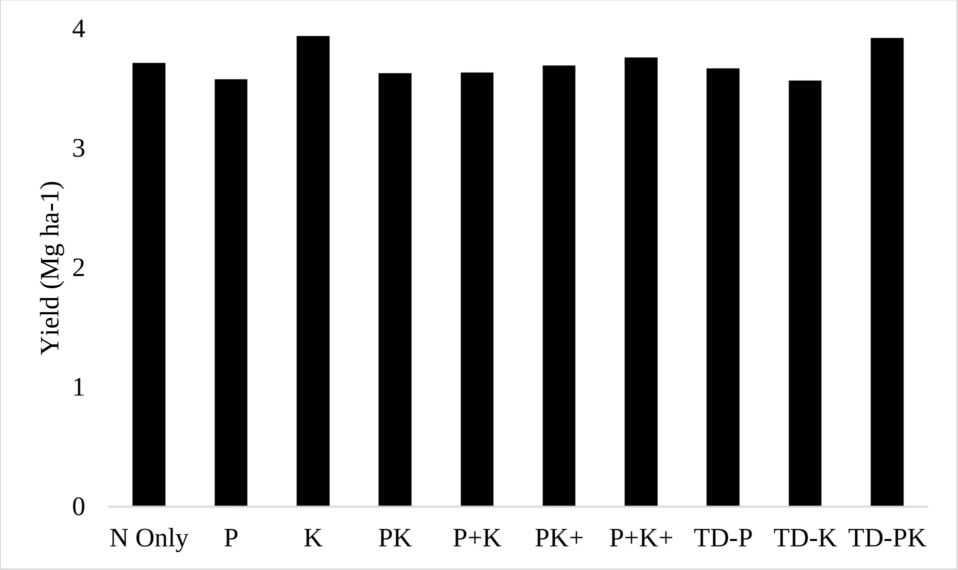


Figure 9. Grain yields, Mg ha^{-1}, from the winter wheat cycle of the 2020-2021 SFFN trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

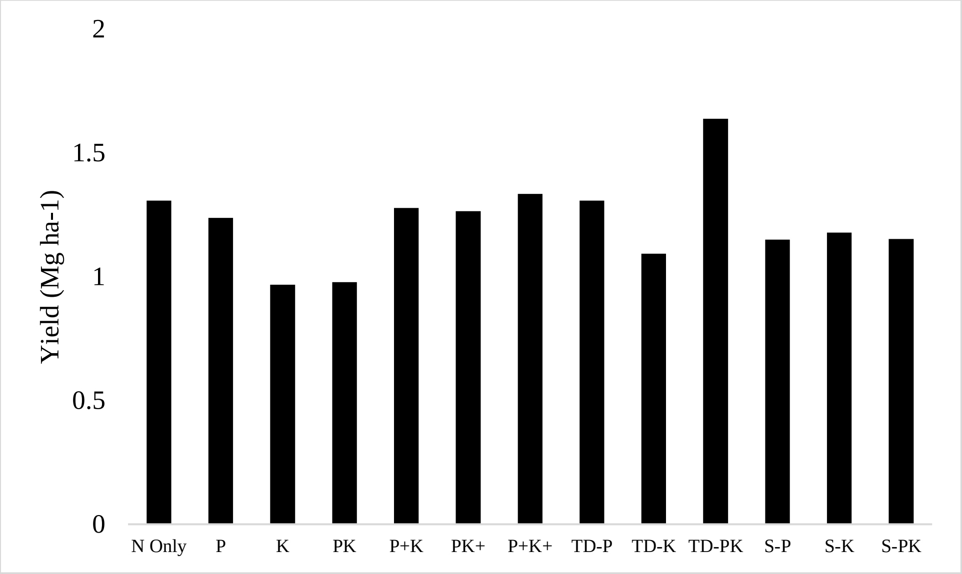


Figure 10. Grain yields, Mg ha^{-1}, from the soybean cycle of the 2020-2021 SFFN trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

Skaggs Family Farm South (SFFS) Lamont, Oklahoma

Soil test M3P and K results for the SFFS 2020-2021 were 9 and 70.5 ppm respectively. These soil test results indicate an 80% P sufficiency and an 85 % K sufficiency for wheat and an 80 % P sufficiency and a 75 % K sufficiency for soybeans (Zhang, et al, 2017). Fertilizer P and K rates for each treatment are provided in table 11.

Table 11. Fertilizer phosphorous and potassium application rates (kg ha^{-1}) of treatments for the SFFS 2020-2021 trial.

Treatment	P	K	PK	P+K	PK+	P+K+	TD-P	TD-K	TD-PK	S-P	S-K	S-PK
P **(kg ha^{-1})**	21.0	0	21.0	37.2	21.0	37.2	37.2	21.0	37.2	37.2	21.0	37.2
K **(kg ha^{-1})**	0	27.8	27.8	27.8	74.1	74.1	27.8	74.1	74.1	27.8	74.1	74.1

Significant differences were observed for the winter wheat at (α) = 0.05, however, no differences were found in the following soybean site. The average winter wheat yield was 3.0 Mg ha^{-1}. The average soybean yield was 1.0 Mg ha^{-1}.

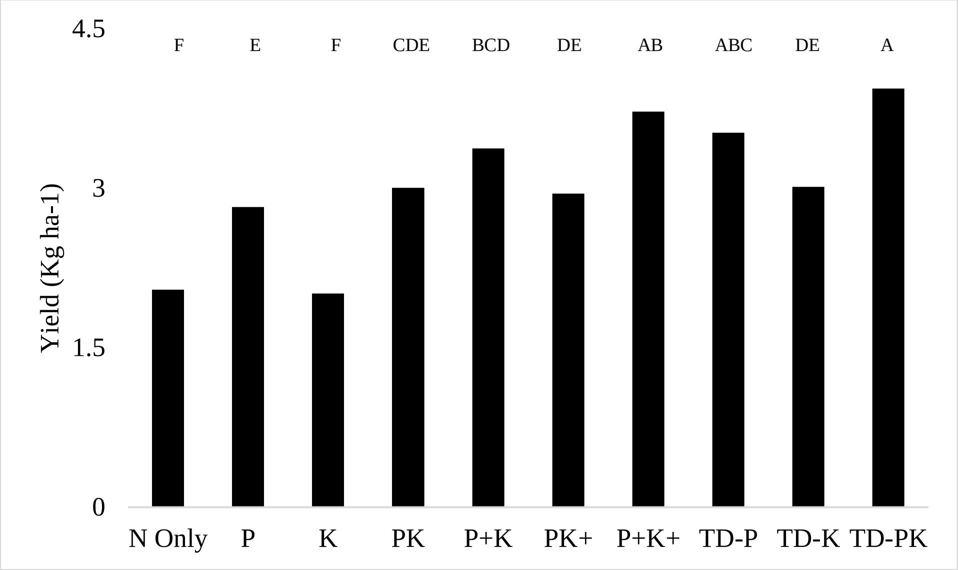


Figure 11. Grain yields, Mg ha^{-1}, from the winter wheat cycle of the 2020-2021 SFFS trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

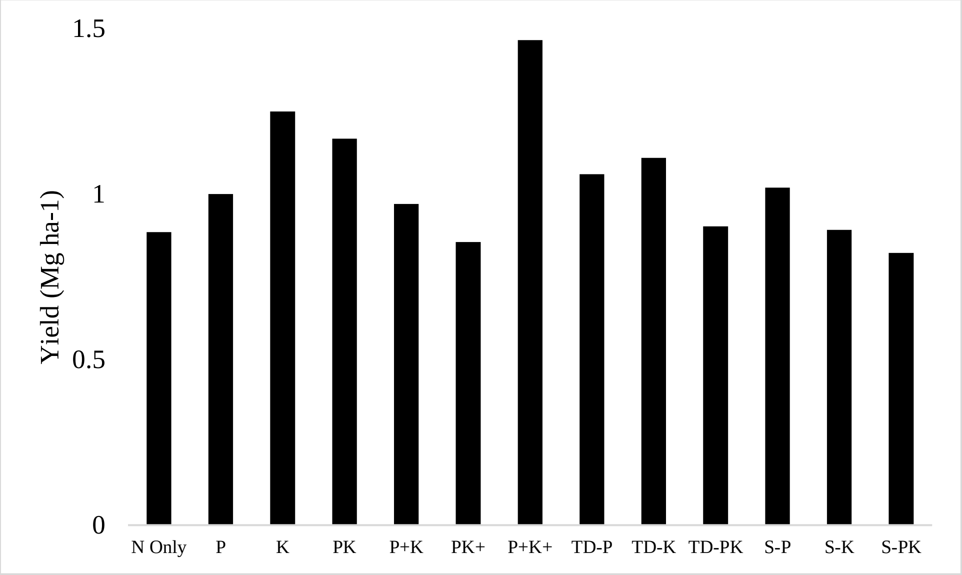


Figure 12. Grain yields, Mg ha^{-1}, from the soybean cycle of the 2020-2021 SFFS trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

Lake Carl Blackwell Research Farm (LCBRF) Perry, Oklahoma

Soil test M3P and K results for the LCBRF 2020-2021 were 11.5 and 99 ppm respectively. These soil test results indicate an 80% P sufficiency and a 95 % K sufficiency for wheat and an 80 % P sufficiency and a 90 % K sufficiency for soybeans (Zhang, et al, 2017). Fertilizer P and K rates for each treatment are provided in table 9.

Table 12. Fertilizer phosphorous and potassium application rates (kg ha^{-1}) of treatments for the LCBRF 2020-2021 trial.

Treatment	P	K	PK	P+K	PK+	P+K+	TD-P	TD-K	TD-PK	S-P	S-K	S-PK
P (kg ha^{-1})	17.6	0	17.6	26.4	17.6	26.4	26.4	17.6	26.4	26.4	17.6	26.4
K (kg ha^{-1})	0	18.5	18.5	18.5	55.6	55.6	18.5	55.6	55.6	18.5	55.6	55.6

No significant yield difference was observed at (α) = 0.05 for either winter wheat or soybeans. The average winter wheat grain yield was 3.7 Mg ha^{-1} across the trial, while the average soybean yield was 2.0 Mg ha^{-1}.

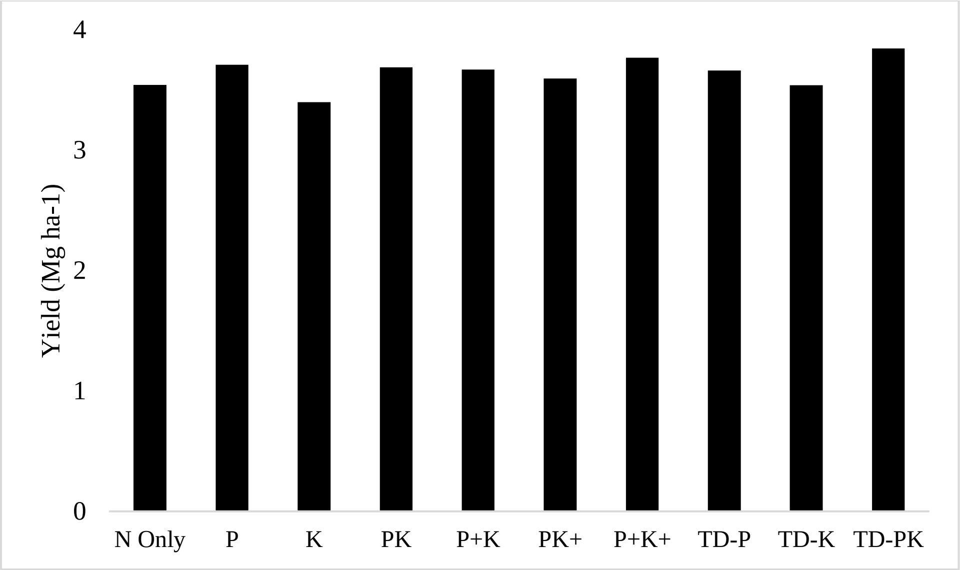


Figure 13. Grain yields, Mg ha^{-1}, from the winter wheat cycle of the 2020-2021 LCBRF trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

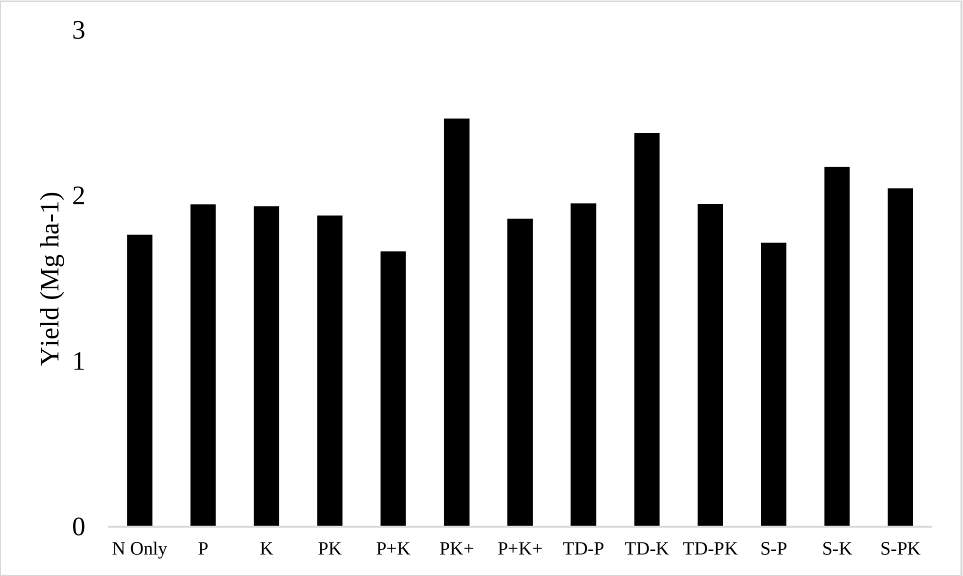


Figure 14. Grain yields, Mg ha^{-1}, from the soybean cycle of the 2020-2021 LCBRF trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

CHAPTER VI

DISCUSSION

All trial locations according to OSU nutrient sufficiency recommendations' were deficient in both P and K (Zhang, et al, 2017). Sufficiency recommendations for 100 % sufficiency are 32.5 ppm and 125 ppm for P and K respectively. Trial locations ranged from 9.0 ppm to 20.5 ppm P and 31.0 ppm to 102.5 ppm K. This represents a range of 80 to 95 % sufficiency for P and a K range from 70 to 95 % sufficiency (Zhang, et al, 2017).

Response to P and K would initially be expected at all locations due to the nutrient deficiencies, however, only three locations showed a significant response due to the application of P or K fertilizer. The ERS 2019-2020 and BFRF locations responded to the application of K and the SFFS 2020-2021 location responded to the application of P. The K response at the ERS 2019-2020 location was not unexpected as a 37.5 ppm soil test K level is only 70 % sufficient (Zhang, et al, 2017). Moisture and favorable growing conditions allowed for the growth of the soybean crop, and additional application of K fertilizer was required. The BFRF location soil test was 102.5 ppm K or 95 % sufficiency. Significant response to the application of K fertilizer was not expected in the wheat crop, however, with average yields of 6.5 Mg ha^{-1}, further K was required to maximize yields. The SFFS location response to P fertilizer application was attributed to a low soil test of 9.0 ppm P (80 % sufficiency) and a 5.4 pH. Additional P fertilizer applications were needed to correct the deficiency of P in the soil, as well as the issues involved with acidic pH levels (Zhang, et al., 2017). A pH of 5.4 allowed otherwise available P to instead be tied up with Al. The addition of P fertilizer increased the availability of P to the soybean crop and alleviated the Al toxicity (Zhang, et al., 2017).

In order to explain why the other three locations; ERS 2020-2021, SFFN, and LCBRF did not have a response to P or K application, other factors must be considered besides only the soil test nutrient levels or pH. The ERS locations for both the 2019-2020 and 2020-2021 years also had pHs of 5.6 and 5.7, yet neither location showed a response to the application of P fertilizer. Once again, the ERS 2020-2021 location had a soil test K value of 31 ppm, less than the 37.5 ppm of the ERS 2019-2020 location that had a response to K application, however, there was no response to K. The LCBRF and the ERS 2020-2021 locations had similar soil test P vales of 11.5 and 10 ppm respectively, compared to the SFFS location that had a soil test P value of 9.0 ppm. The SFFS location had a response to P application, while the formerly mentioned locations did not, all with very similar soil test P values. In previous work by Reed and Arnall (2021) comparing farmer practice to nutrient-rich strips in double-crop fertility studies, only 20 out of 244 comparisons showed any significant differences. Lower than average yields compounded with hand harvesting increase error when determining differences between treatments, and thus differences potentially could have been found in more locations if in a higher-yielding environment.

Excluding the ERS locations, soybean yields did not reach their maximum yield potential due to a lack of moisture during the critical R3-R4 stages of the soybean plant when nutrient uptake is most rapid (Bender, et al., 2015). A study conducted in northern China found that water-deficient soils inhibited plant root growth, reduced absorbing areas of plant roots, and decreased nutrient uptake (Li, et al., 2009). The only soybean crop to show significant yield differences was the ERS 2019-2020 location. This could have been due to more available moisture to place applied P and K fertilizer into the soil and available to the crop increasing nutrient efficiency (Li, et al., 2009). The figure from the Oklahoma Mesonet (Figure 11) reports the average plant-available water in the top 10.2 cm of soil at the ERS for the 2020 soybean crop. Plant available water during late summer months never dropped below 25 mm, allowing soybean development to occur unaffected.

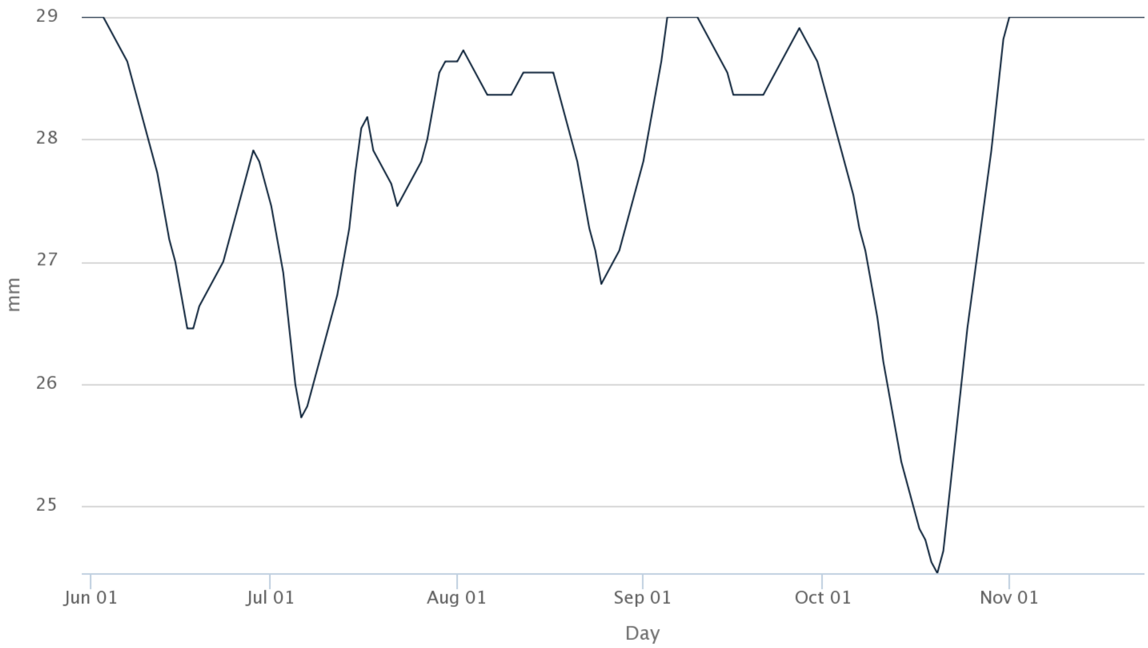


Figure 15. Plant available water in the top 10.2 cm of soil at the ERS during the 2020 soybean cycle. Available water is measured in (mm).

Oklahoma precipitation levels decrease from east to west (Ford, et al., 2015). Figure 12 below adapted from (Ford, et al., 2015), represents the annual precipitation (mm) in Oklahoma, as well as illustrates the changing precipitation gradient from east to west. The black dots represent mesonet stations. The BFRF and the LCBRF locations are both found in drier zones of Oklahoma compared to the ERS locations.

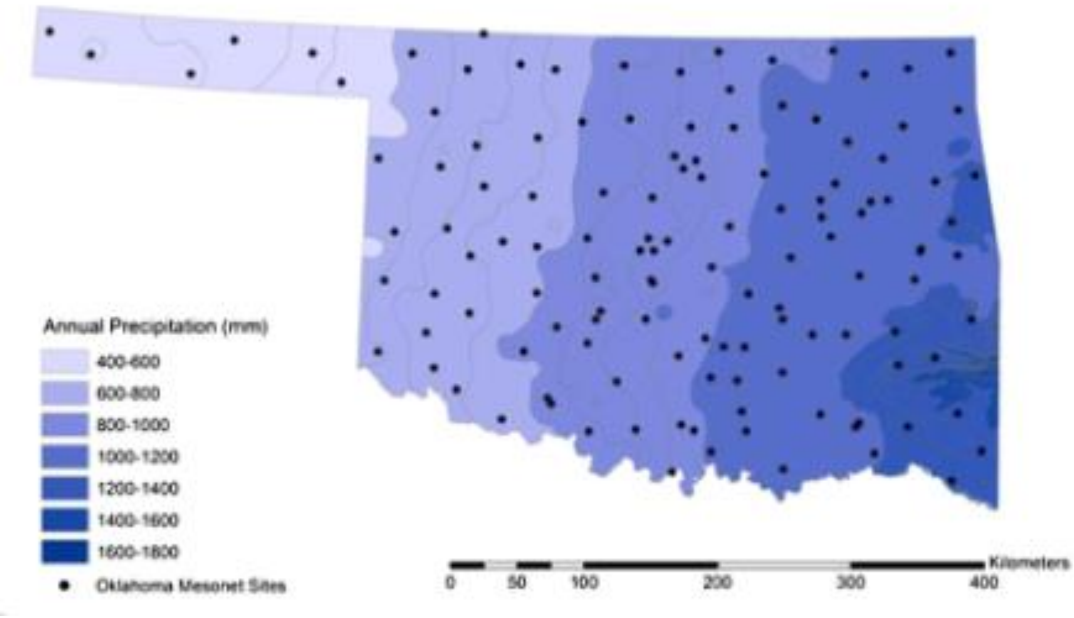


Figure 16. Adapted from (Ford, et al., 2015), represents the annual precipitation (mm) in Oklahoma, as well as illustrates the changing precipitation gradient from east to west. The black dots represent mesonet stations.

In these drier conditions, significant spatial changes in soil type became evident inside the BFRF and the LCBRF locations, with one soil reacting poorer to drought conditions. In addition to stunting soybean root growth to depth, root angle and root branching density are also affected in drought conditions (Kunert et al., 2016). It is hypothesized that impacts of summer drought conditions influenced the crop, and the magnitude of the impact was influenced by soil characteristics. The Mesonet station located near Newkirk, within 11 km of the BFRF site, reported 83.44 cm of rainfall for 2020. However, the area only received 5.87 cm of rainfall during August and September, a critical time for soybean pod filling. The figure from the Oklahoma Mesonet (Figure 13) reports the average plant-available water in the top 10.2 cm of soil at BFRF. Plant available water during late August and early September was near zero, negatively affecting soybean development.

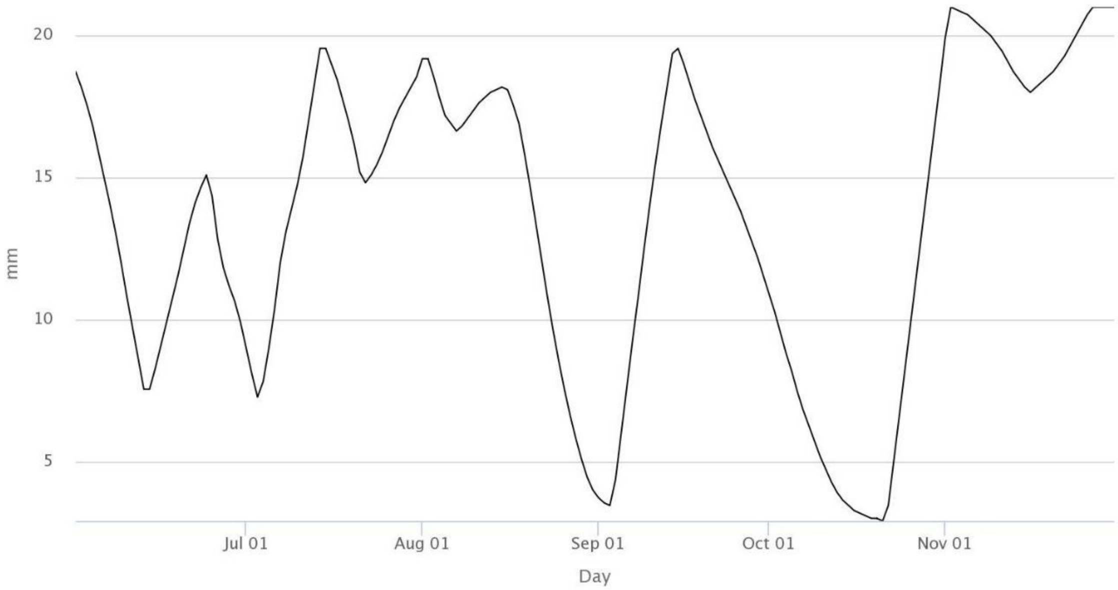
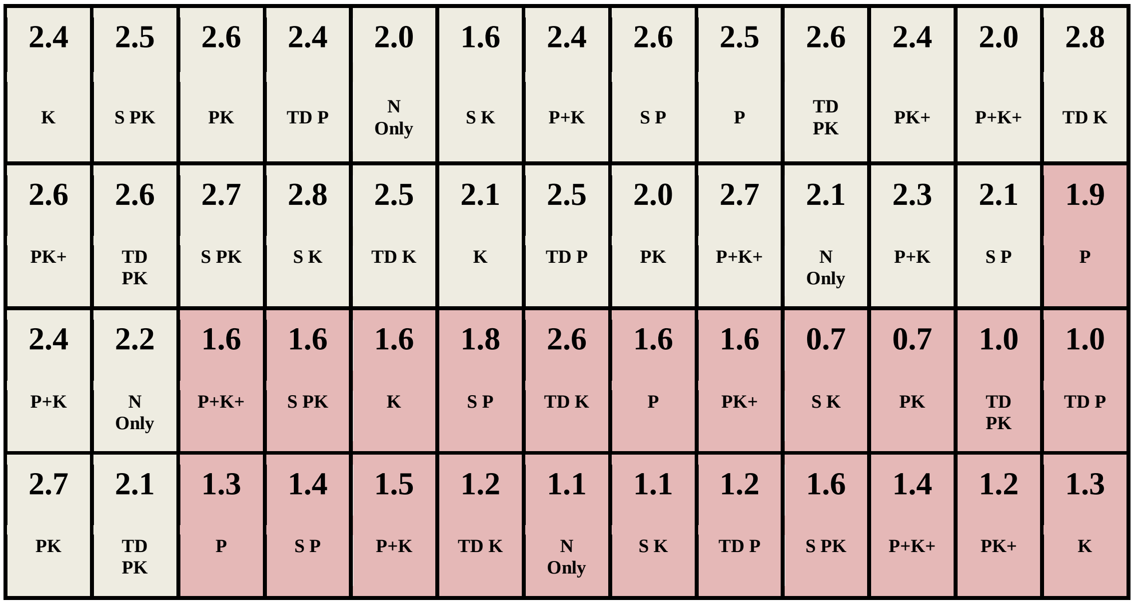


Figure 17. Plant available water in the top 10.2 cm of soil at the BFRF during the 2020 soybean cycle. Available water is measured in (mm).

As suspected, a soil texture change was discovered that dissected the trial from southwest to northeast within the BFRF location. An Agra-Foraker complex made up the southeast section and a Foraker-Pawhuska complex made up the northwest section. It is hypothesized that a restricting layer in the Agra-Foraker complex soils showed drought symptomology earlier in the season and reduced soybean yields were a result. Soil texture between the two soils was also different, as the Agra-Foraker soil's topsoil was a silt loam compared to a clay loam for the Foraker-Pawhuska. A study conducted to understand the influence of texture on moisture characteristics of soil concluded that the available water capacity of a soil positively correlated with increases in silt and decreased with increases in sand (Salter, et al., 1966). It can be hypothesized that even smaller clay particles compared to silt could hold even more water, thus the Foraker-Pawhuska soils could hold more moisture for the soybean crop. The Agra- Foraker soils averaged a yield of 1.4 Mg ha^{-1}, compared to the Foraker-Pawhuska soils which had an average yield of 2.4 Mg ha^{-1}. A trend of increased yields due to the application of P and K, averaging 2.5 Mg ha-1, in comparison to the N-only treatment (2.1 Mg ha-1) occurred in the Foraker-Pawhuska soil. This suggests that at minimum the P and K applied for the winter wheat crop also benefited the soybean crop. Unfortunately, the variability induced by the drought stress and soil type variance prevented any significant identification of treatment impact. The figure below (Figure 14) represents the change in soil type inside the trial location and the resulting yield differences due to the soil type changes.



2.4 K	2.5 S PK	2.6 PK	2.4 TD P	2.0 N Only	1.6 S K	2.4 P+K	2.6 S P	2.5 P	2.6 TD PK	2.4 PK+	2.0 P+K+	2.8 TD K
2.6 PK+	2.6 TD PK	2.7 S PK	2.8 S K	2.5 TD K	2.1 K	2.5 TD P	2.0 PK	2.7 P+K+	2.1 N Only	2.3 P+K	2.1 S P	1.9 P
2.4 P+K	2.2 N Only	1.6 P+K+	1.6 S PK	1.6 K	1.8 S P	2.6 TD K	1.6 P	1.6 PK+	0.7 S K	0.7 PK	1.0 TD PK	1.0 TD P
2.7 PK	2.1 TD PK	1.3 P	1.4 S P	1.5 P+K	1.2 TD K	1.1 N Only	1.1 S K	1.2 TD P	1.6 S PK	1.4 P+K+	1.2 PK+	1.3 K

Figure 18. The BFRF location experienced drought conditions during the soybean growing season. A soil type texture change became evident due to the drought conditions. The Foraker-Pawhuska complex soils (white) in the northwest section of the location yielded consistently better than the Agra-Foraker complex soils (pink) in the southeast section. Each rectangle represents an individual plot. The top number represents yield (Mg ha^{-1}) and the bottom letters represent treatment based on Table 3 in methodology.

Hexum and Boxley (1986) state that at least 76.2 cm of annual precipitation is needed to ensure a successful double cropping system. The LCBRF received 74.8 cm throughout the 2021 year, however, only 11.99 cm of rainfall fell during July and August, critical for the soybean crop. While irrigation was applied, (5.72 cm) it was limited and did not mitigate the impact of heat and drought. The figure from the Oklahoma Mesonet (Figure 15) reports the average plant-available water in the top 10.2 cm of soil at LCBRF.

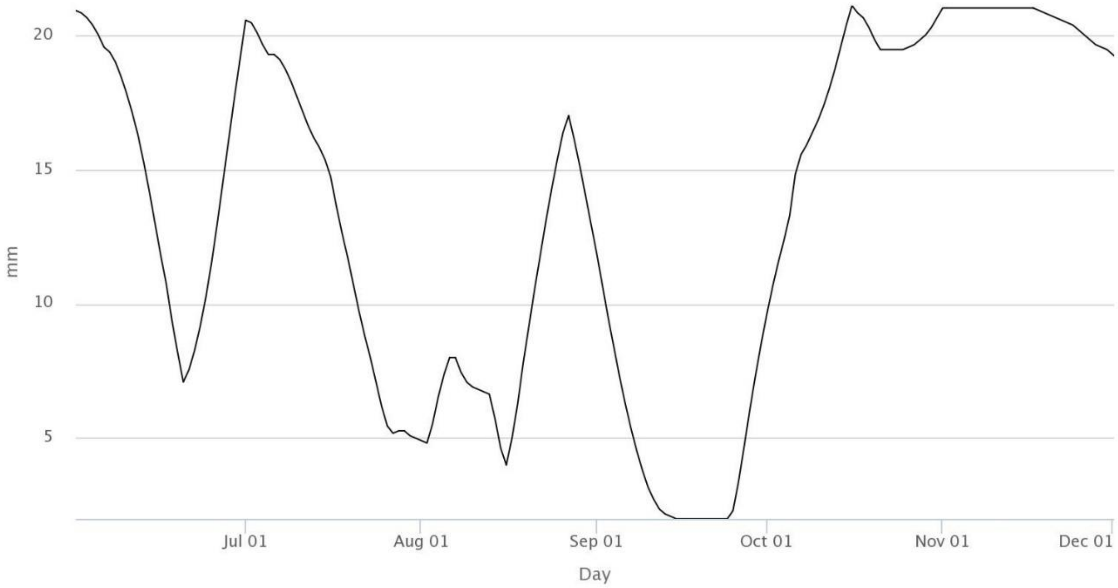
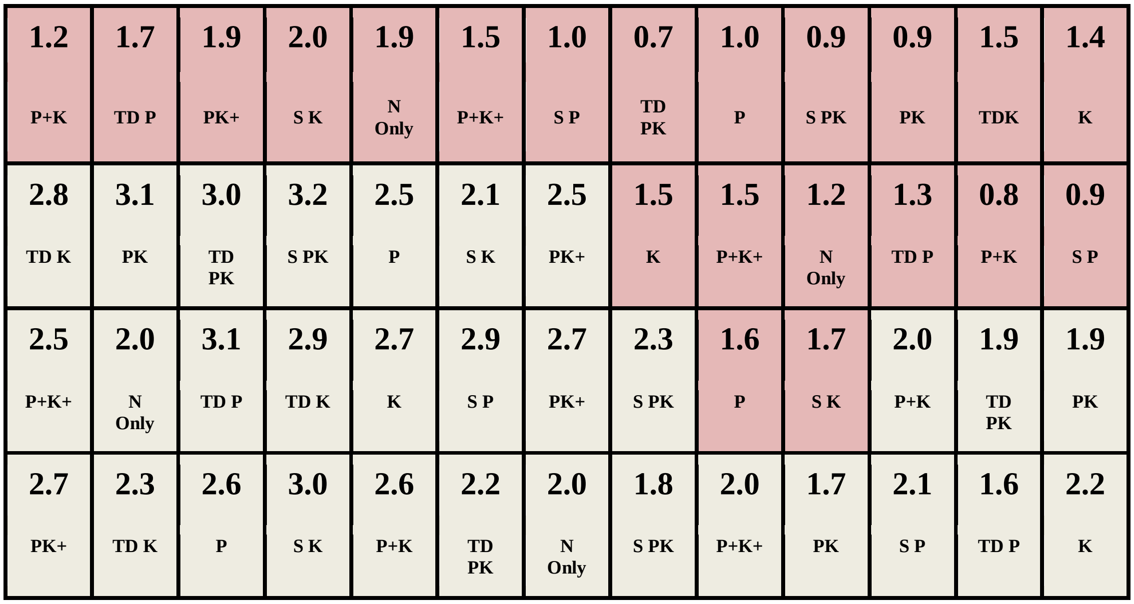


Figure 19. Plant available water in the top 10.2 cm of soil at the LCBRF during the 2021 soybean cycle. Available water is measured in (mm).

A soil type change is believed to have caused lower yields on the east-southeast side due to a limiting layer in Port-Oscar soils. Better yields were recorded on the west-northwest in Pulaski fine sandy loam soils. The Port-Oscar soils averaged a yield of 1.3 Mg ha^{-1}, compared to the Pulaski soils which had an average yield of 2.4 Mg ha^{-1}. The figure below (Figure 15) represents the change in soil type inside the trial location and the resulting yield differences due to the soil type changes.



1.2 P+K	**1.7** TD P	**1.9** PK+	**2.0** S K	**1.9** N Only	**1.5** P+K+	**1.0** S P	**0.7** TD PK	**1.0** P	**0.9** S PK	**0.9** PK	**1.5** TDK	**1.4** K
2.8 TD K	**3.1** PK	**3.0** TD PK	**3.2** S PK	**2.5** P	**2.1** S K	**2.5** PK+	**1.5** K	**1.5** P+K+	**1.2** N Only	**1.3** TD P	**0.8** P+K	**0.9** S P
2.5 P+K+	**2.0** N Only	**3.1** TD P	**2.9** TD K	**2.7** K	**2.9** S P	**2.7** PK+	**2.3** S PK	**1.6** P	**1.7** S K	**2.0** P+K	**1.9** TD PK	**1.9** PK
2.7 PK+	**2.3** TD K	**2.6** P	**3.0** S K	**2.6** P+K	**2.2** TD PK	**2.0** N Only	**1.8** S PK	**2.0** P+K+	**1.7** PK	**2.1** S P	**1.6** TD P	**2.2** K

Figure 20. The LCBRF location experienced dry conditions during the soybean growing season. A soil-type texture change became evident due to the dry conditions. The Pulaski fine sandy loam soils (white) in the west-northwest section of the location yielded consistently better than the Port-Oscar soils (pink) in the east-southeast section. The top number represents yield (Mg ha^{-1}) and the bottom letters represent treatment based on Table 3 in methodology.

CHAPTER VII

CONCLUSION

The winter wheat double-crop soybean system is an increasingly popular choice for Oklahoma producers considering changing climate conditions and strong commodity prices for both winter wheat and soybeans. While a significant response to the application of P and K was limited, the results show that there are environments in which the wheat crop can benefit from additional P and K fertilizer applied for the soybean crop. In the case of the soil with low M3P and an acidic soil pH, the additional P applied during the winter wheat growing season, intended for soybeans, alleviated the aluminum toxicity issues with acidic pH, increasing wheat yields. Beyond the single location with low soil test P and pH no other significant response was found to the addition of and P. This may be explained in that most locations were only marginally deficient P and the majority of the varieties used in the study were considered to have acid soil tolerance. As was mentioned prior Penn and Arnall (2015) found that cultivars with aluminum tolerance had increased P use efficiency. The BFRF location showed a significant wheat grain yield response to the K fertilization, but the additional K applied for the soybean crop showed no benefit for the wheat crop. While there was no significant increase in soybean grain yield to the additional K fertilizer observations suggest that the application of K fertilizer for soybeans may be of benefit. As was mentioned before the double-crop system is susceptible to yield-limiting conditions, heat, and moisture, due to the maturity of the crop during the peak summer months. The soybean grain yields achieved in this study were all below the previous five-year yield average for all the locations. The low achieved yields and crop stress may have limited this study’s ability to identify a significant response to the application of fertilizer. More work is needed in the study of double-crop soybean fertility management. The addition of more environments into this data set is necessary for a better understanding and proper recommendation for double-crop soybean fertilization strategies.

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APPENDICES

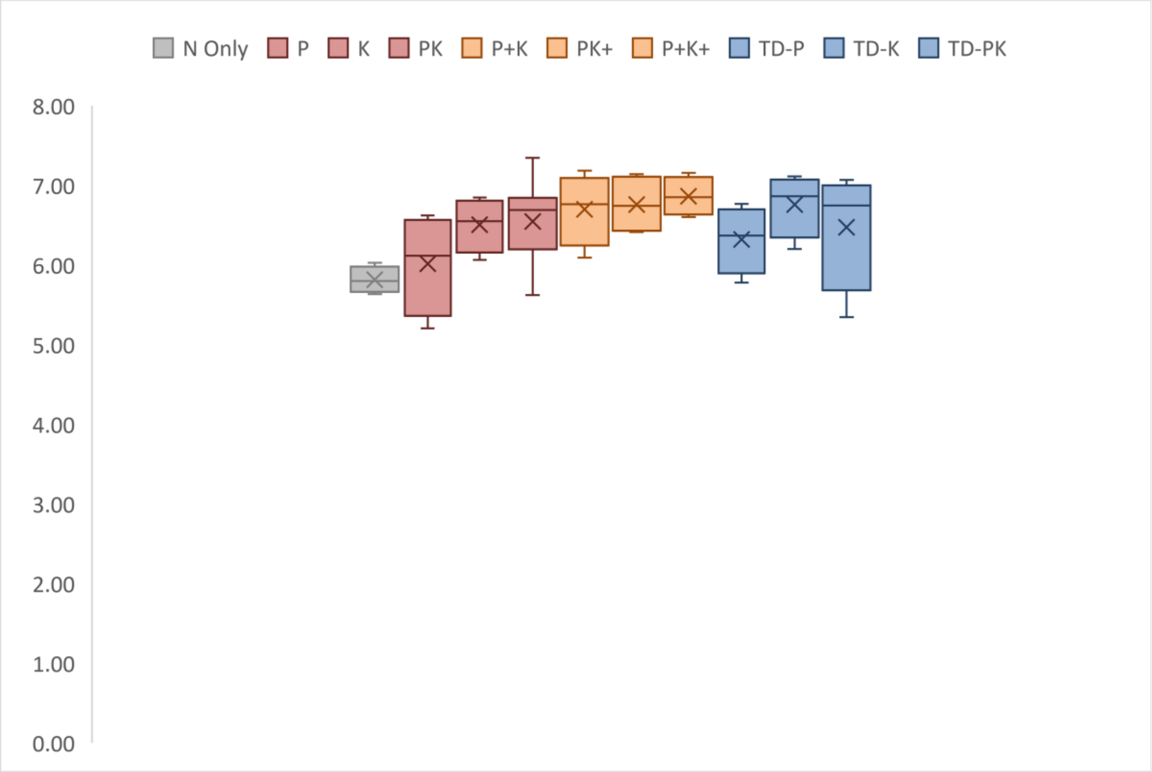

Figure 21. Grain yields, Mg ha^{-1}, from the wheat cycle of the 2019-2020 BFRF trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

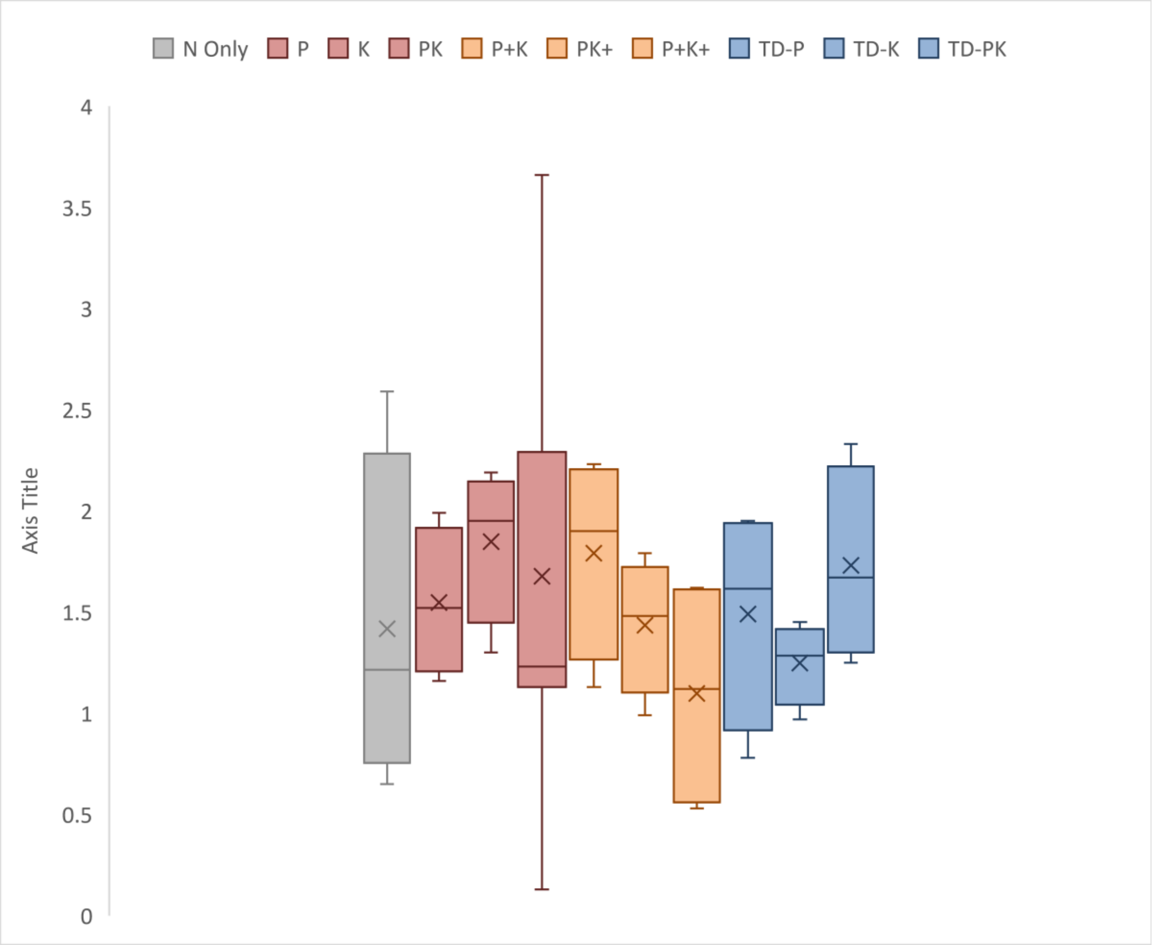

Figure 22. Grain yields, Mg ha^{-1}, from the wheat cycle of the 2020-2021 ERS trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

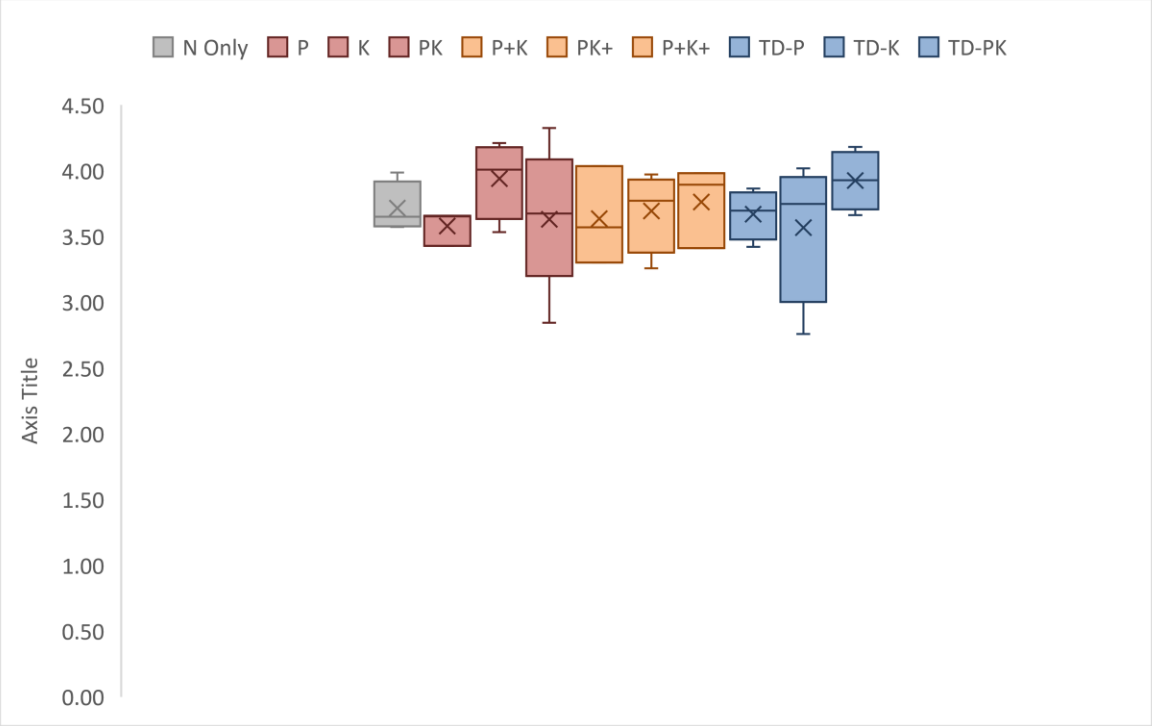

Figure 23. Grain yields, Mg ha^{-1}, from the wheat cycle of the 2020-2021 SFFN trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

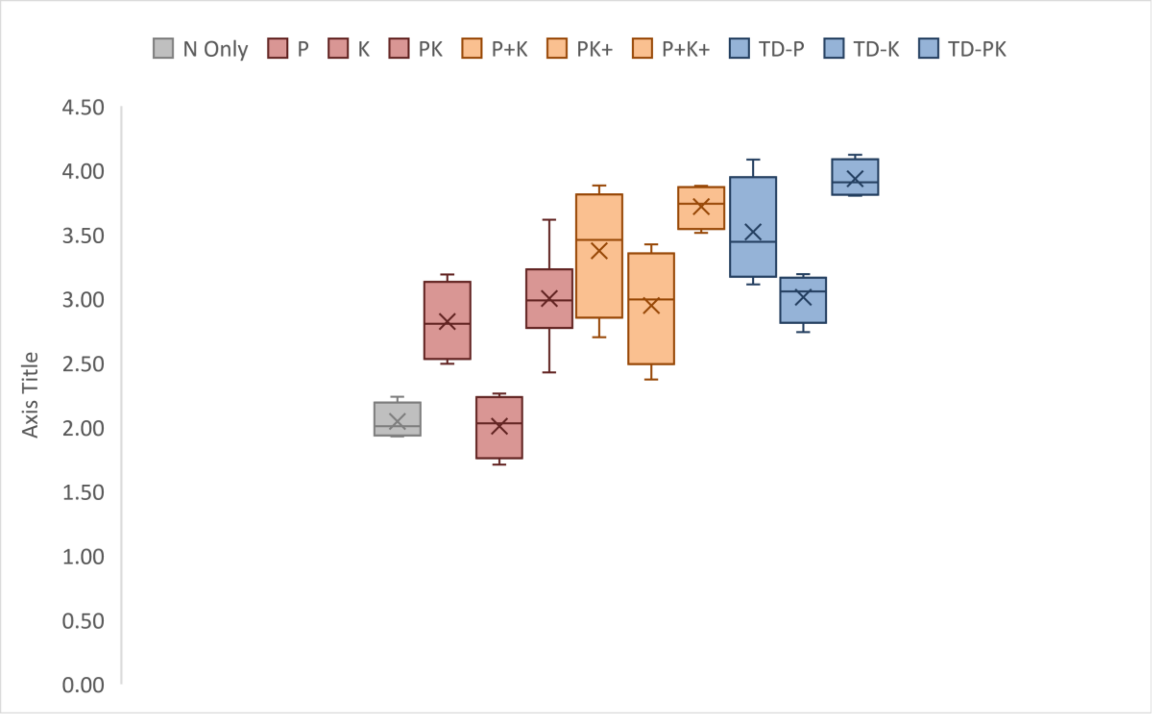

Figure 24. Grain yields, Mg ha^{-1}, from the wheat cycle of the 2020-2021 SFFS trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

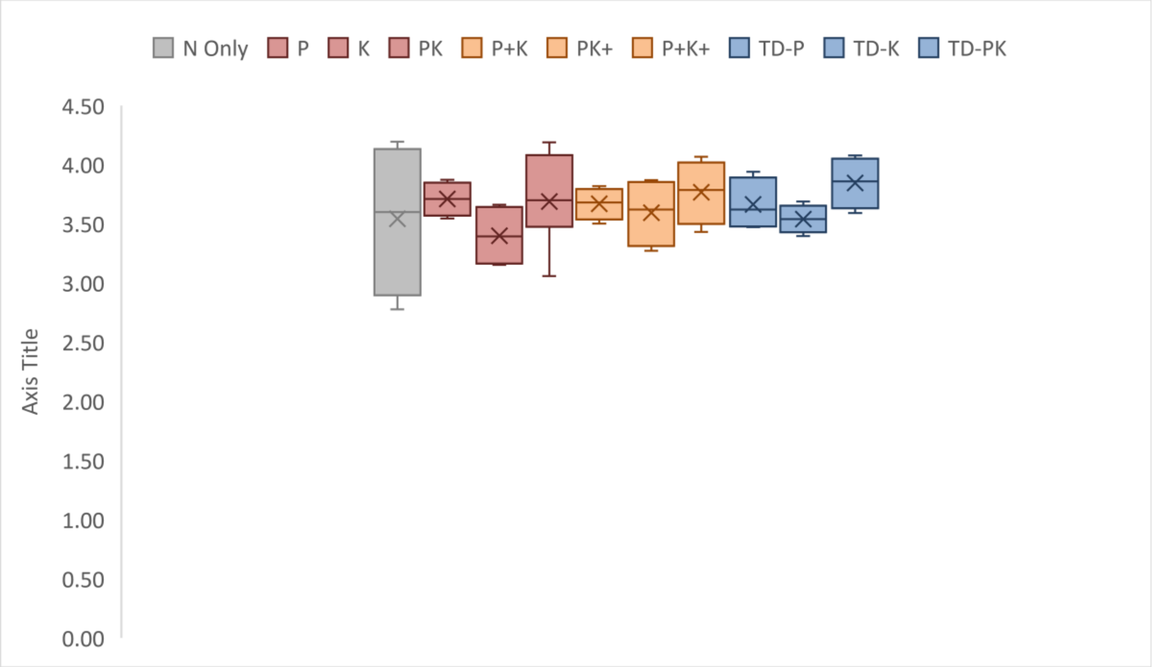

Figure 25. Grain yields, Mg ha^{-1}, from the wheat cycle of the 2020-2021 LCBRF trial. Treatments include timings of phosphorus and potassium applications based upon preplant wheat soil test results. Treatments with different letters denote significant statistical difference at Alpha = 0.05.

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