ABSTRACT

MILES, LYDIA C. Phosphorus and Potassium Fertilization for High-Yielding Soybeans in North Carolina. (Under the direction of Dr. Luke Gatiboni).

In North Carolina, soybean crop yields have increased in the last decade without an increase to the nutrient recommendations provided through the North Carolina Department of Agriculture and Consumer Services soil (NCDA & CS) testing lab. Achieving high yields requires attentive management to monitor and supply the quantity of nutrients necessary so that soil fertility is not a limiting factor in production. To address this issue, we conducted a set of trials in eight locations over three years, selecting fields with historically high yields with medium to very high soil test availability of phosphorus (P) and potassium (K). The objectives of this study were: a) to investigate the need for higher rates of P and K for soybean fields producing over 4000 kg ha^{-1}; b) to investigate the ideal levels of P and K in soybean plant tissue collected from high yielding soybean fields c) to determine the exportation of P and K by analyzing the grain from the high yielding environments. Various rates of P and K were tested in each site year. In general, K fertilization increased the in-season availability of K in the soil but it was less evident for P fertilization. No statistically significant yield response to the increased P and K levels were observed in soils with P and K levels above the current critical soil test values (CTSV) recommended by NCDA&CS. Therefore, the current North Carolina soil test recommendations are adequate for high yielding soybeans, as long as the field begin the season with a P and K above the CSTV.

Phosphorus and Potassium Fertilization for High-yielding Soybeans in North Carolina

by
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BIOGRAPHY

Lydia Carroll Miles (Oswald), was raised in Short Pump, Virginia. Following high school she attended Clemson University where she obtained a B.S. in Crops Science (Agronomy) with a minor in Plant Pathology. During her free time she was an active member of the Clemson Equestrian Team and Agronomy Club. Following her graduation in 2017, Lydia accepted a position as the Assistant Director of Gilcrease Orchard in Las Vegas, NV. In October of 2018 Lydia accepted a position as a Field Crops Extension Agent in Columbus County, North Carolina. In Fall of 2020 Lydia began pursuing a Master of Science in the field of Soil Fertility under the supervision of Dr. Luke Gatiboni. During this time she continued working full time as an extension agent in Columbus County and also welcomed a daughter to the world with her husband, Mitchell. Upon completing this degree Lydia plans to continue to serve the farmers and stakeholders of Columbus County in her role as an Extension Agent.

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LITERATURE REVIEW

The Importance of Soybeans

Soybeans play a vital role in agriculture in the United States as well as worldwide. According to the USDA (2015), 70% of the soybeans produced in the United States are used for animal feed. Soybeans are a great option for livestock feed as they provide a high-quality protein source and are generally easily digestible. Of the remaining 30% of soybeans produced in the U.S., 15% are used for human consumption via cooking oils, tofu, soy milk and more (USDA, 2015). The remaining 15% is used for biodiesel and industrial products (USDA, 2015).

The USDA (2023) reports that the United States is the second largest producer of soybeans worldwide growing roughly 28% of the world's soybeans. Brazil currently produces the largest amount of soybeans growing 40%, while Argentina comes in third producing 12%. This means that the top three soybean producing countries grow 80% of the crop in the entire world.

In the United States, the average yield for 1994 was 2421 kg ha^{-1} increasing to 3363 kg ha^{-1} in 2021 (USDA, 2023). While those are average yields, farmers using intensive management can achieve much higher yield levels. For example, the 2022 NC soybean yield contest winner yielded 6759 kg ha^{-1} on irrigated ground and 6644 kg ha^{-1} on unirrigated ground (NC Extension, 2023). Yields in North Carolina have seen a steady increase with time. In 2002, the average yield seen in the North Carolina soybean yield contest was 3161 kg ha^{-1}, while by 2019 the average yield assessed in the yield contest had risen to 5582 kg ha^{-1} (Vann et al., 2021). With higher yields it is expected to see soybeans require larger amounts of nutrients, making soil fertility management an important factor in sustaining higher yields.

The Importance of Soil Fertility for High-Yielding Environments

Nearly all of the land suitable for agriculture is already being cultivated and the world's population continues to grow. To continue to support the growing population and avoid a food crisis it is necessary to find ways to increase the yields in land under cultivation. One such way to increase yield is through improving and maintaining soil fertility.

The Food and Agriculture organization of the United Nations defines soil fertility as the ability of a soil to sustain plant growth by providing essential nutrients (FAO, 2023). Managing these essential nutrients requires the quantification of crop nutrient requirements and the nutrient-supplying capacity of the soil. Both crop nutrient requirements as well as the nutrient supplying capacity of the soil can be identified through a proper soil testing program (Havlin et al., 2013; Hardy et al., 2014).

Research into soil testing began in England around 1845 by a scientist named Charles Daubney (Anderson, 1960). Since then, work in the soil testing field quickly grew in importance and by the 1940s it was beginning to be recognized as an important part of any successful agronomic operation (Anderson, 1960). The North Carolina Soil Testing Division was established in 1938 and hastily grew through work with farmers and neighboring agronomic agencies. By the early 1950's North Carolina's farmers were using appropriate rates of fertilizer and doing so in a much more efficient way than farmers in surrounding states (NCAGR, 2007). The primary reason NC farmers had altered the way they apply nutrients is due to soil test results. Soil test results provide the most effective way to fertilize without sacrificing yield but also without wasting money or harming the environment through over application of nutrients

(Corey, 1987; Brown, 1987). One of the basic rules of nutrient management is to set the nutrient rates to meet the crop requirements.

Phosphorus and Potassium as Essential Nutrients

Of the macronutrients required for plant growth (N, P, K, calcium, magnesium, and sulfur) N, P, and K are considered primary macronutrients because they are very often applied as fertilizers (Havlin et al., 2013). In North Carolina, soil test recommendations for N are based on the total amount of N required by the plant in the growing season, considering the yield expectation, soil type, and region. Soil analysis is not used to assess N availability due to the high leaching potential occurring in North Carolina. Conversely, P and K fertilizer recommendations are entirely based on the soil analysis. The amount of fertilizer recommended for phosphorus and potassium aims to increase nutrient levels up to the CSTV (Hardy et al., 2014).

As an essential nutrient, P helps encourage root growth and formation; it can affect the quality of the fruit, seed, and flower formation. Phosphorus is also responsible for energy transport, storage, and use and is required for normal N fixation (Bang et al, 2021). Soybeans require relatively high amounts of P, especially through growth stage R3-beginning pod (Bender et al., 2015). Phosphorus deficiency symptoms vary widely but may present with spindly growth and small leaflets. These leaves may turn dark green or blue green and normal plant development is delayed (Bang et al., 2021).

Plants can absorb P from soil in the form of phosphates. The exact phosphate they absorb is dictated by environmental conditions, mainly pH and growing medium (Halul and Hassan, 2023). Worldwide many soils are deficient in P, however in North Carolina we have built a high

reserve of legacy P through fertilization of agricultural soils over the decades (Gatiboni et al., 2021). Legacy P occurs when excess is applied such that the soil-test P is above the CSTV and become stable in soil due to various chemical reactions and occlusion to minerals and organic matter (Gatiboni et al., 2020).

Potassium helps plants to overcome drought stress, and improves the rigidity of plant stalks. It is necessary for osmotic and ionic regulation and is an activator of different enzymes. Additionally, K can regulate the availability of other nutrients in the plants (Kuntyastuti et al. 2019). Deficiency symptoms will present as a decrease in the number and size of leaves and eventually the size of the plant and principally, necrosis on the tip and along the margins of leaves (Bang et al., 2021; Pettigrew W.T., 2008). Soybeans require high levels of potassium for optimal growth, similar to many other species of bean (Kuntyastuti et al., 2019).

Unlike P, K build-up in the soil is less common because plants export a higher amount of K and this nutrient is prone to leaching in coarse-textured soils. Therefore, the management of K fertilization should equalize the soil reserves, the plant requirement, and the leaching potential (Crozier et al., 2004).

Uptake of Phosphorus and Potassium by Soybeans

Nutrient uptake by plants will vary based on the growth stage. In soybeans, the uptake rates can be divided into three stages. The first stage is slow uptake- during the first 30 days following emergence when the plants are just getting started and nutrient uptake is slow. The second uptake stage is maximum uptake. This occurs when the plant is growing rapidly- generally between R2 and R5 (full bloom- beginning seed fill.) The third and final stage of uptake is slow uptake. After the plants reach mid-pod fill its needs for nutrients also lessen and

some nutrients are redistributed from the vegetative parts of the grain (Harper, 1971; Usherwood 1998; Bender et al., 2015).

For North Carolinas conditions, Osmond and Kang (2008) state soybeans export 5.82 mg P kg^{-1} of grain. For potassium, the exports are 20.56 mg K kg^{-1} of grain. Using this logic, a soybean field yielding 3360 kg ha^{-1} (50 bu $acre^{-1}$) would export 19.55 kg P ha^{-1} (17.4 lb $acre^{-1}$) and 69.08 kg K ha^{-1} (61.6 lb $acre^{-1}$). Maintaining the same concentration of P and K in the grain, if a high-yielding field yields 4704 kg ha^{-1} (70 bu $acre^{-1}$) representing an increase of 40% in yield, it would be expected for P and K exports to reach 27.4 kg P ha^{-1} and 96.7 kg K ha^{-1}. However, newer literature published in the last decade shows that demand of P and K by modern varieties of soybean could be higher than the older varieties (Filippi et al., 2021; Neto et al., 2021), which would increase the nutrient exports beyond the values predicted earlier.

In data obtained from 2015 to 2019, Filippi (2021) found that on average 5.5 mg P kg^{-1} of grain and 17.6 mg K kg^{-1} of grain are removed. Further Filippi (2021) found that more recent roundup ready varieties use 18% more K than older non-roundup ready varieties. This indicates that modern varieties of soybeans not only yield higher but also accumulate more nutrients in the process. A study by Neto et al. (2021) further solidified modern soybean genetics higher need for nutrients. Neto (2021) found that modern varieties remove 26.9% more P and 45% more K than historical varieties.

Soil Test Correlation and Calibration

According to McGrath et al. (2014), a good soil testing program must have two aspects: 1) an accurate laboratory procedure to estimate the soils fertility and 2) adequate correlation and calibration data to be able to recommend accurate fertility measures. Sabbe & Marx (1987) and

Corey (1987) state the development of a soil test for a specific nutrient generally involves three steps. First, the extractant must be chosen. Second, the amount of nutrient extracted (i.e., test value) must be correlated with the amount of nutrient taken up by the plant and the yield response. Third, the test value must be calibrated to translate soil test values to a recommended rate of fertilizer to achieve a certain yield. This means that correlation and calibration are the two most important steps in making an accurate soil test-based recommendation for fertilizer application (Slaton et al., 2022). Correlation is the first part of the process. It identifies the plant nutrient requirements for a growing season by correlating the yield to a given soil testing method (Mitchell and Mylavarapu, 2014). Using correlation studies, it is possible to calculate the CSTV, which is the value beyond which no yield response to fertilization is expected (Slaton et al., 2021). The calibration process aims to determine the crop fertilizer requirement at different soil test values below the CSTV (Mitchell & Mylavarapu, 2014; McGrath et al, 2014; Slaton et al., 2021). The calibration of a soil test determines how much nutrient must be added in order to reach the CSTV and have the opportunity to produce optimum yield. These two aspects-correlation and calibration come together and allow us to make accurate fertility recommendations.

When establishing the fertilizer recommendations, there are two common approaches to managing soil fertility. The sufficiency model, and the build and maintain model (McGrath et al., 2014). The sufficiency method aims to provide the amount of nutrients necessary to support the crop at optimum growth without providing any extra to establish a reserve in the soil. The primary goal of the sufficiency method is to maximize profitability while minimizing inputs (Macnack, 2017). The build and maintain method provides nutrients in excess of what the crop need in order to establish a soil nutrient reserve.

Critical Soil Test Values of Phosphorus and Potassium for North Carolina

An important part of determining the probability of crop response to fertilizers is through determining the CSTV. The CSTV for a crop nutrient is the value at which the relative yield stops increasing with increased fertilization. Applying fertilizer above the critical value will not result in an increase in yield and instead will cause a decrease in profit due to unnecessary use of additional product. Generally, it is not profitable to apply a fertilizer after you have reached roughly 90 to 95% of potential yield is reached. It is important to note that CSTV can vary among different locations, weather conditions, clay content, and crop species (Gatiboni et al., 2021). For this reason, generally CSTVs are conservative to avoid limitations by low nutrient content in the soil.

In North Carolina, the general CSTV for phosphorus is currently established as 60 mg dm^{-3} and potassium at 98 mg dm^{-3} (Hardy et al., 2014). However, the values found in the literature vary for specific site and years. Cox (1992) found a CSTV of P for soybeans varying from 18 to 58 mg dm^{-3} in data collected between 1985 and 1989. Similarly, Cox (1996) found values from 31 to 35 mg dm^{-3} in data obtained from 1991 to 1993. When considering correlation and calibration studies in North Carolina with other row crops like corn, wheat, cotton, and peanuts, the CSTV of P varied from 4 to 42 mg dm^{-3} (Cox, 1992; Cox, 1996; Cox and Barnes, 2002; Cox and Lins, 1984; Crozier et al., 2004; Kamprath, 1999; Shelton et al.,1961). Despite the CSTVs historic range, that averaged between 20 and 40 mg dm^{-3} , North Carolina adopted a modified sufficiency approach, establishing the CSTV of P at 60 mg dm^{-3}. With that decision, North Carolina has the highest CSTV of any of the southern states (Zhang et al. 2021). For K, there is less data available, but Crozier et al. (2004) reported CSTV of K in North Carolina historically ranged from 39 to 141 mg dm^{-3} and the current CSTV is set at 98 mg dm^{-3}.

Recently, Morales et al. (2022) determined the CSTV of P and K using long-term soil fertility trials in North Carolina. The CSTV of P ranged from 14 mg dm^{-3} (Piedmont) to 66 mg dm^{-3} (Coastal Plain) and the CSTV of K ranged from 49 to 93 mg dm^{-3}. These values represent a significant increase when compared to the historical CSTVs for P mentioned before. It may indicate that the higher yields obtained by Morales et al. (2022) are pushing up the CSTV. For this reason, it is important to study high-yielding soybean environments in North Carolina to determine if the current CSTVs of P and K are adequate for the yield levels obtained in the state.

In closing, it is evident that soybean yield has continued to increase substantially over the last several decades. Additionally, it seems that higher yielding modern varieties of soybeans are removing more nutrients from the soil than their historic counterparts. Because of this, it is necessary to conduct further research to determine if alterations to North Carolinas CSTV need to be made in an effort to support the nutrient exports of high-yielding growth environments.

MATERIALS AND METHODS

Experimental Design

The study was conducted at eight total sites over a three-year span, from 2020 to 2022. These field locations were in Bertie, Columbus, Beaufort, Washington, and Pender counties in the Coastal Plain Region and Union (2 sites) and Rowan Counties in the Piedmont Region. On-farm sites and Research Stations were used to host the study. Soil type, weather conditions, management practices, variety planted, etc. varied on a site-by-site basis and the crop management followed the practices adopted by the host farm or research station. Fields were selected based on their yield potential, with history of producing high yields (over 3362 kg ha^{-1}). Trials were located across the main agricultural production regions of North Carolina: Tidewater, Piedmont, and Coastal Plain to represent a variety of different environmental and weather conditions. Table 1 shows the site information for all eight sites including region, soil series and texture.

Table 1. Site information for all trial site years

Year	County	Site Code	Region	Predominant Soil Series	Soil Texture
2020	Union	UNI20	Piedmont	Cid Channery	Silt Loam
2020	Beaufort	BEA20	Tidewater	Roanoke	Fine Sandy Loam
2021	Columbus	COL20	Coastal Plain	Norfolk	Loamy Fine Sand
2021	Union	UNI21	Piedmont	Cid Channery	Silt Loam
2021	Pender	PEN21	Coastal Plain	Noboco	Loamy Fine Sand
2021	Washington	WAS21	Tidewater	Arapahoe	Fine Sandy Loam
2022	Bertie	BER22	Coastal Plain	Goldsboro and Lynchburg	Sandy Loam
2022	Rowan	ROW22	Piedmont	Lloyd	Clay Loam

1. Soil series and texture according to Web Soil Survey based on GPS site coordinates.

Two trials were installed in each site-year. One trial tested rates of P fertilizers and another tested rates of K fertilizers. The rates of P and K are presented in Tables 2 and 3. The trials were arranged in a randomized complete block design with four replications. In the P treatments, a blanket rate of K was applied to all plots (101 kg K_2O ha^{-1} at BEA20, 140 kg K_2O ha^{-1} at UNI20, and 112 kg K_2O ha^{-1} in the other site-years). In the K treatments, a blanket rate of Pwas applied to all plots (101 kg P_2O_5 ha^{-1} at BEA20, 126.1 kg P_2O_5 ha^{-1} at UNI20, and 84.06 kg P_2O_5 ha^{-1} in the other site-years). The sites BEA20 had only four P treatments because the available field was smaller than anticipated and four plots (highest P treatment) were dropped. The site UNI20 had rates of P and K higher than the usual tested range because the farm host reduced the row spacing during the planting, reducing the size of the plots and, consequently, increasing the fertilizer rate applied per area.

All of the treatments were applied within two days of planting via broadcast spreading.

Table 2. Phosphorus treatments in the eight site-years

Treatment	BEA20	UNI20	COL21	UNI21	PEN21	WAS21	BER22	ROW22
	kg P_2O_5 ha^{-1}							
P1	0	0	0	0	0	0	0	0
P2	33.6	42.0	28.0	28.0	28.0	28.0	28.0	28.0
P3	67.3	84.1	56.0	56.0	56.0	56.0	56.0	56.0
P4	101.0	126.1	84.1	84.1	84.1	84.1	84.1	84.0
P5	-	168.1	112.1	112.1	112.1	112.1	112.1	112.1

BEA20 = Beaufort County 2020; INI20 = Union County 2020; COL21 = Columbus County 2021; UNI21 = Union County 2021; PEN21 = Pender County 2021; WAS21 = Washington County 2021; BER22 = Bertie County 2022; ROW22 = Rowan County 2022

Table 3. Potassium treatments in the eight site-years

Treatment	BEA20	UNI20	COL21	UNI21	PEN21	WAS21	BER22	ROW22
	kg K_2O ha^{-1}							
K1	0	0	0	0	0	0	0	0
K2	56.0	70.0	56.0	56.0	56.0	56.0	56.0	56.0
K3	112.0	140.1	112.1	112.1	112.1	112.1	112.1	112.1
K4	134.5	210.2	168.1	168.1	168.1	168.1	168.1	168.1
K5	224.2	280.2	224.2	224.2	224.2	224.2	224.2	224.2

BEA20 = Beaufort County 2020; UNI20 = Union County 2020; COL21 = Columbus County 2021; UNI21 = Union County 2021; PEN21 = Pender County 2021; WAS21 = Washington County 2021; BER22 = Bertie County 2022; ROW22 = Rowan County 2022

Each field was soil sampled at planting before the application of treatments to establish the baseline fertility. The results of the initial soil fertility status of each site are presented in Table 4, where it is observed that all sites had medium to high fertility. The P availability ranged from 52 mg dm^{-3} to 205 mg dm^{-3} and the K availability ranged from 48 mg dm^{-3} to 156 mg dm^{-3}.

As the soil test critical values of P and K in North Carolina are 60 and 98 mg dm^{-3} (Hardy et al, 2014), none of these sites required high rates of P and K fertilizers. Actually, for most of them, P and K fertilizers were not recommended.

All of the trial sites were planted via direct seeding and the fertilizers. Planting dates for the five of the eight trial sites were between late-April and mid-May during the optimal planting window for high-yielding soybeans. Three sites were planted mid-June due to double cropping or logistical reasoning; these sites are UNI20, PEN21, and BER22. Table 5 lists the management practices for each site including the variety of soybeans planted, the maturity group, the planting date and seeding rate, the row spacing of the plot, and the tillage practices. If the field was no-till than the residue present was also noted. Figures 1, 2, and 3 present the weather conditions registered for each site-year at the closest weather station.

Table 4. Initial soil test data

	2020 Trial Sites		2021 Trial Sites				2022 Trial Sites	
	BEAU20	**UNI20**	**COL21**	**PEN21**	**UNI21**	**WAS21**	**ROW22**	**BER22**
HM(%)	0.86	0.41	0.31	0.67	0.37	3.50	0.32	1.00
W/V(g/cc)	1.05	0.93	1.24	1.24	0.77	0.88	0.94	1.18
BS (%)	80.1	74.0	79.5	68	77.6	84.5	80.8	84.8
Ac (mEq 100cc^{-1})	1.88	1.41	0.69	1.25	1.43	2.30	1.45	0.93
CEC (mEq 100cc^{-1})	9.39	5.48	3.83	3.85	8.93	14.75	7.78	6.20
pH	5.57	5.40	5.98	5.43	6.01	5.99	5.98	6.13
Concentration of P and K in soil (mg dm^{-3})								
P	80.2	53.0	74.7	148.0	205.3	101.2	138.5	51.5
K	80.5	47.8	117.7	96.0	88.0	92.2	156.3	101.3

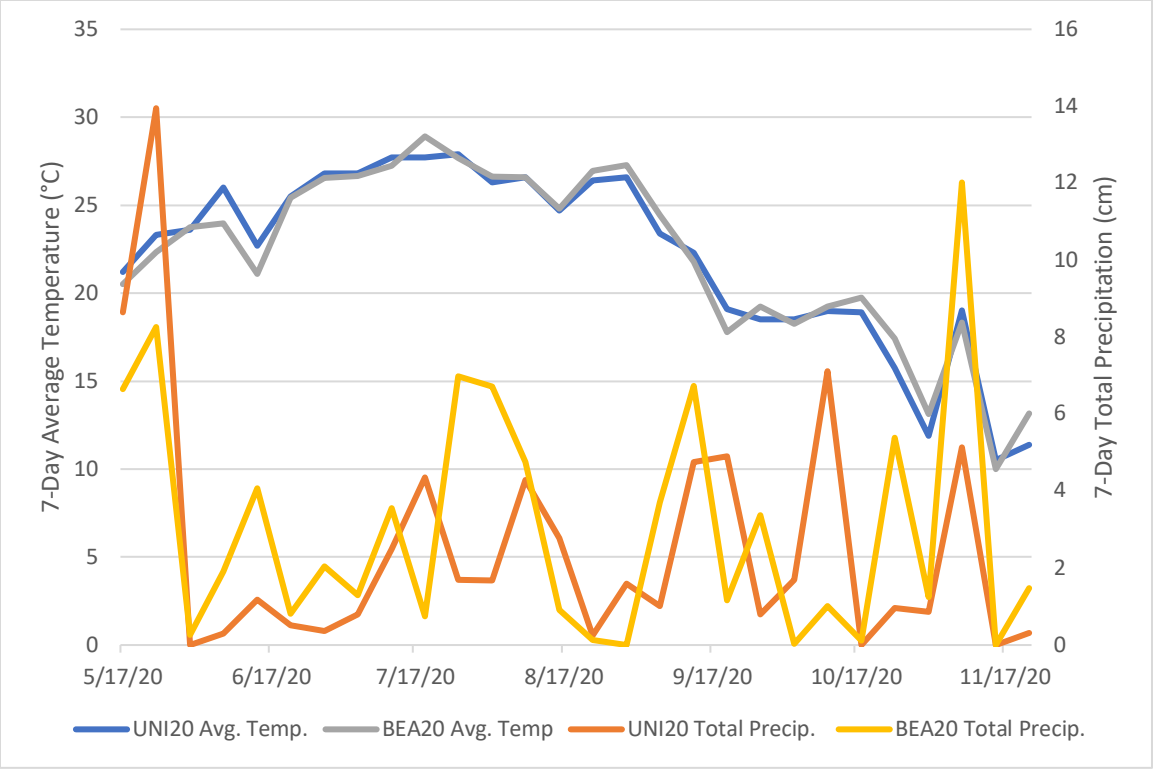


Figure 1. 2020 seven-day average air temperature and seven-day total precipitation.

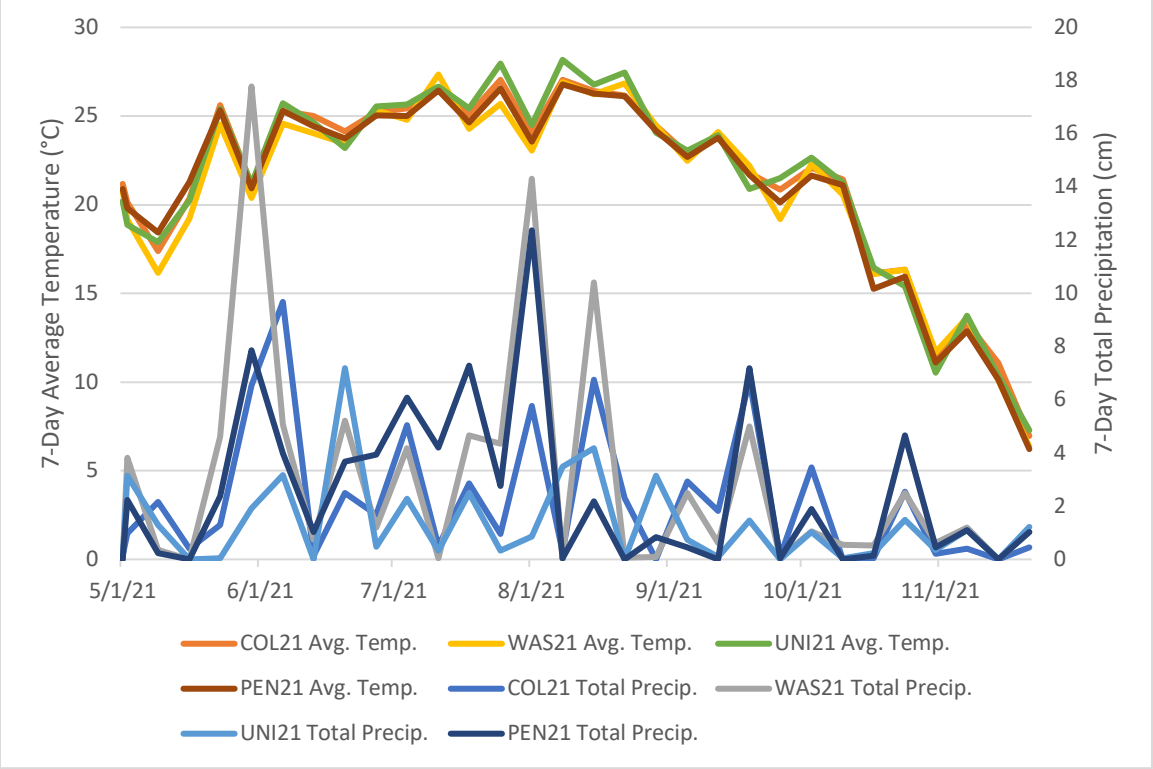


Figure 2. 2021 seven-day average air temperature and seven-day total precipitation.

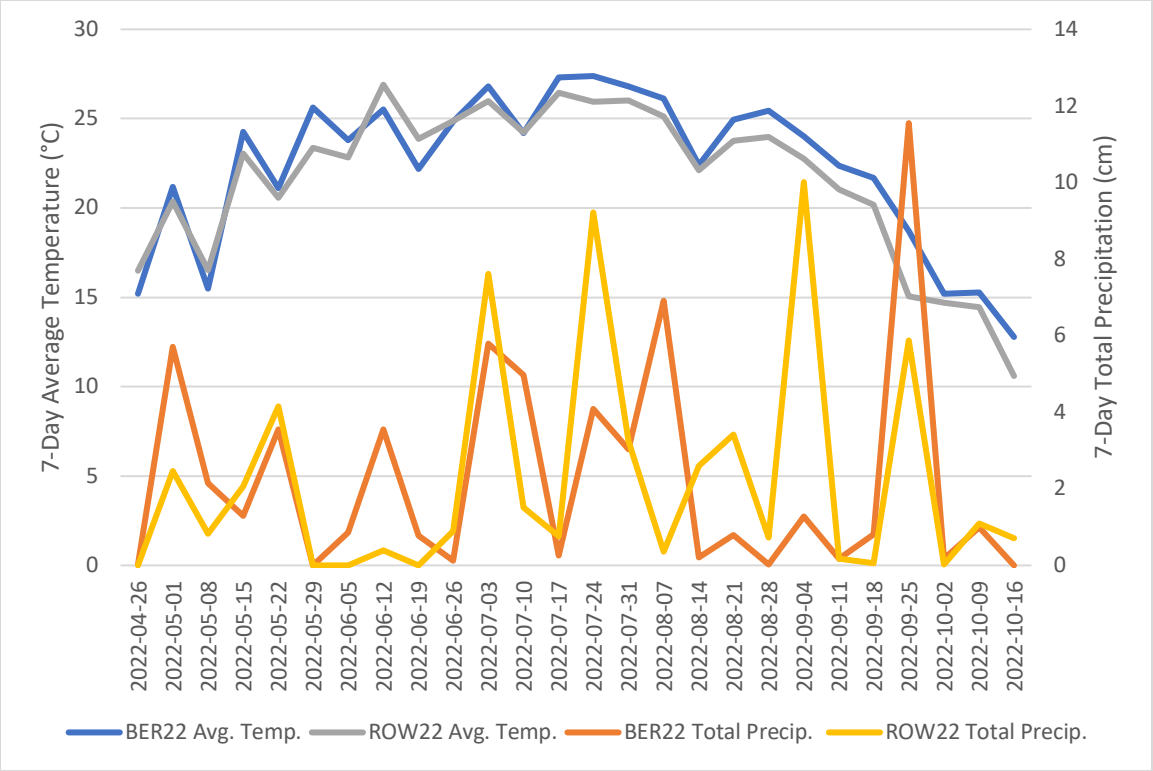


Figure 3. 2022 seven-day average air temperature and seven-day total precipitation.

Table 5. Variety and management information

Site year/location	Variety	Maturity Group	Planting Date	Seeding Rate kg ha^{-1}	Row Spacing	Tillage practice and residue if present
UNI20	Pioneer 55A49X	5.5	6/26/2020	300,000	.30m	Conventional
BEA20	MorSoy 4846	4.8	05/15/2020	300,000	.91m	Conventional
PEN21	CP7221X	7.2	06/18/2021	300,000	.38m	No-till Wheat Residue
COL21	AG57XF1	5.7	05/04/2021	300,000	.91m	Conventional
WAS21	P46A20LX	4.6	04/27/2021	269,500	.76m	Conventional
UNI21	AG59XF0	5.9	04/27/2021	321,100	.76m	Conventional
BER22	Foundation 15-5007		06/15/2022	269,500	.91m	Conventional
ROW22	P48A60X	4.8	04/26/2022	305,200	.76m	No-till Wheat Residue

Data Collection

At least one month into plant growth, soil samples were taken from each plot at each site location. Samples were collected using a 20cm long x 1.9cm diameter soil probe inserted to a depth of 10cm at the no-till sites and 20cm at the conventional tillage sites. Soil samples were sent to the NCDA&CS soil testing lab for fertility analysis using the Mehlich-3 extraction method. Once the plants reached growth stage R1 (beginning bloom) plant tissue samples were taken from 15-20 trifoliate leaves of the uppermost mature leaves per plot. These samples were collected from the innermost rows to eliminate edge effects. The tissue samples were sent to the NCDA&CS for nutrient content analysis. Harvest was performed at natural maturity. At harvest, yield data was collected from the innermost rows of each plot via a combine yield monitor and yield was corrected for the moisture content. A single exception was made for the Columbus site in 2021. This site suffered from green stem which prevented adequate dry down necessary for the combine to properly harvest the grain. Instead, 10 whole plants were taken from the innermost rows of each plot through random selection. Yield calculations were then made based on the amount of grain taken from those 10 plants using the plant population to scale and then corrected for moisture content. The grain samples were then sent to the NCDA&CS or the Environmental and Agricultural Testing Service (EATS Laboratory, NCSU) to determine the levels of P and K in the grain.

Statistical Analysis

Data from each site location was analyzed separately due to variations in treatments and growth conditions in each site using JMP statistical software (JMP®, Version *17 Pro*. SAS Institute Inc., Cary, NC, 1989–2023) to perform the analysis. A standard least squares model was constructed to determine the effects of treatment and replication on P and K variables such as

concentration of nutrient in the plant tissue sampled at R1, concentration of nutrient in harvested grain, the amount of grain harvested, and the amount of each nutrient exported. Before statistical analysis, a small number of data points were removed due to missing samples or combine issues during harvest. If there were significant results as indicated by a P-value of less than .05 an LSMeans Differences Tukey HSD test was conducted to compare treatments.

Outliers in the data sets were analyzed in JMP through the quartile method. The median value is the measure of center and the interquartile range divided by 1.34898 is the measure of spread. This calculation results in the spread corresponding to one standard deviation. The K sigma value is set to three and will determine outliers as three times the spread away from the center. Because the spread is one standard deviation this method will identify outliers that are three standard deviations away from the center. Outliers were removed from the data sets.

RESULTS AND DISCUSSION

Yield Response to Phosphorus Rates

In this study, a high yielding site was defined as one that yields higher than 4000 kg ha^{-1}. Five of the eight sites tested were high yielding environments by that definition (Figure 4 and 5).

According to USDA-NASS, the average soybean yield in Union County in 2020 was 3134 kg ha^{-1} (USDA-NASS, 2023). In our field site in Union County (UNI20), yield ranged from 4046 to 4325 kg ha^{-1} with an average yield of 4192 kg ha^{-1} across all treatments. There were no statistically significant differences in the yield between P rates. The reason for lack of response to P fertilization was due to the adequate level of P available in that field prior to treatment. UNI20 had a soil P concentration of 53 mg dm^{-3}. The critical soil test value recommended by NCDA&CS is 60 mg dm^{-3} (Hardy et al., 2014) but Gatiboni et al. (2021) emphasize the historical data collected in multiple trials in North Carolina over the last 60 years show in general crops do not respond to P fertilization when the soil test P (STP) is higher than 30 to 40 mg dm^{-3}.

According to USDA-NASS, the average soybean yield at Beaufort County in 2020 was 3201 kg ha^{-1} (USDA-NASS, 2023). Soybean yield at BEA20 ranged from 4030 to 4204 kg ha^{-1} with an average across all treatments of 4145 kg ha^{-1}. Prior to treatment BEA20 had a P concentration of 80 mg dm^{-3} which is above the current CSTV for North Carolina and no P fertilization would have been recommended in accordance with a NCDA&CS soil test. As expected, there was no significant differences in yield between treatments at the BEA20 site.

According to USDA-NASS, the average soybean yield at Columbus County in 2021 was 2387 kg ha^{-1} (USDA-NASS, 2023). The yield at COL21 ranged from 5603 to 7086 kg ha^{-1} with an average of 6361 kg ha^{-1} and no yield difference among the treatments. Initial soil data from COL21 showed a P concentration of 75 mg dm^{-3} in soil, meaning no response to treatments was

expected due to the initial STP being above the CSTV. It is important to note that the yield data is abnormally high at this site. However, this site was harvested by hand due to green stem disorder, preventing harvesting with a plot combine. So, the method used to determine the yield from these plots may not have been accurate. The important take away from this site-year is not the level of yield but instead that there was no statistically significant difference in the yield between treatments.

Yield at PEN21 ranged from 2759 to 3851 kg ha^{-1} with an average of 3064 kg ha^{-1}. Even with such a wide range, there was no significant difference in yield between the treatments. Initial soil data for PEN21 showed a P concentration of 148 mg dm^{-3}. This is considered a "very high" level by the NCDA&CS. According to the USDA-NASS, the average soybean yield in Pender County in 2021 was 2871 kg ha^{-1} (USDA- NASS, 2023). PEN21 was not considered a high yielding site as defined in this experiment as a yield of higher than 4000 kg ha^{-1}. This is primarily due to the fact that PEN21 is a double-cropped site and, therefore, had a later planting date. Morris et al. (2021) noted that yields are lower in a double crop planting due to a shorter period of time for vegetative growth and reduced light capture. Later planting situations tend to result in smaller plants with fewer pods (Morris et al., 2021, Purcell et al., 2002).

UNI21 was our lowest yielding site across all site years, with yields ranging from 2611 to 2778 kg ha^{-1} and an average of 2654 kg ha^{-1} across all treatments. Similar to other site-years, there was no significant difference in the yield between treatments. UNI21 had the highest initial P concentration of any of the eight site-years with a value of 205 mg dm^{-3}. According to the current state recommendations, no P fertilization would have been recommended for UNI21. According to USDA NASS, the average soybean yield in Union County in 2021 was 3060 kg ha^{-}

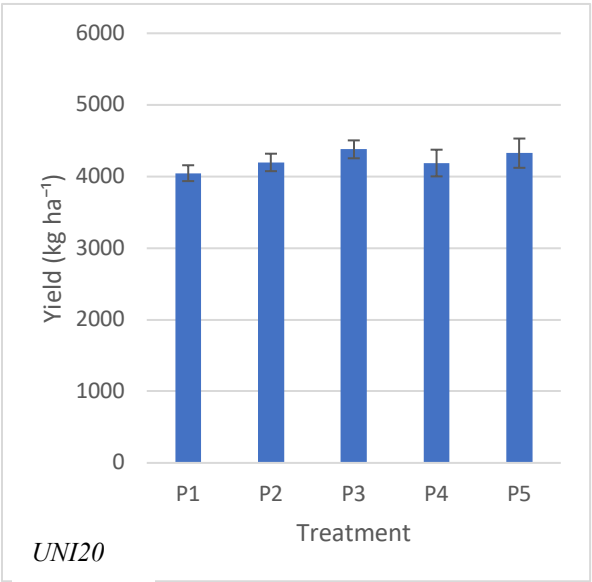
$^{-1}$ (USDA-NASS, 2023) and the lower yields obtained in our study are a consequence of a late-season infestation of frogeye leaf spot disease.

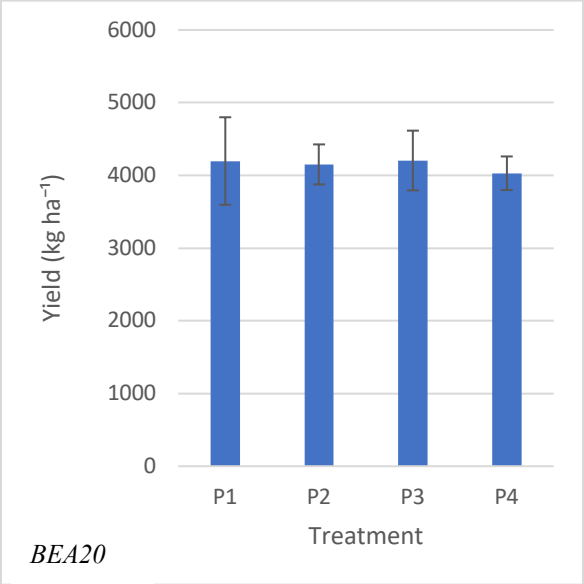
Yield at WAS21 ranged from 4074 to 4729 kg ha^{-1} and the average across all treatments was 4405 kg ha^{-1}, above the average of 3430 kg ha^{-1} estimated by the USDA-NASS for Washington County in 2021 (USDA-NASS, 2023) There was no significant difference in yield between treatments. This site had an initial soil test value of 100 mg dm^{-3} and no P fertilization would have been recommended (Hardy et al., 2014).

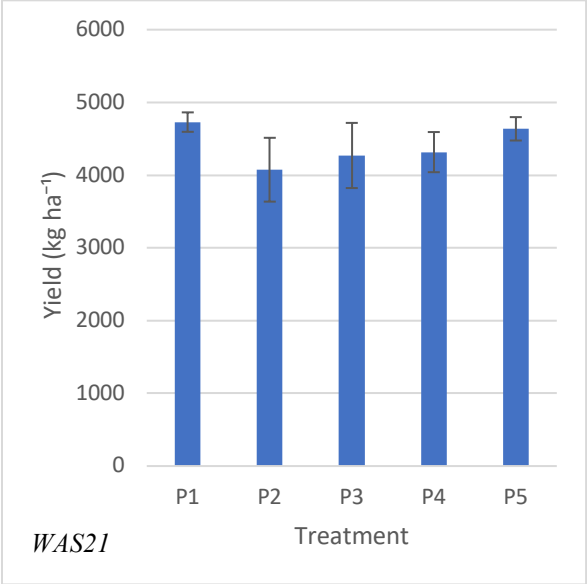
According to USDA-NASS, the average soybean yield at Bertie County in 2022 was 2475 kg ha^{-1} (USDA-NASS, 2023). The BER22 site had yields ranging from 2621 to 2713 kg ha^{-1} with an average across all treatments of 2673 kg ha^{-1}. There was no significant difference in yields between the treatments. Initial soil test data for BER22 showed a P concentration of 51 mg dm^{-3}, which is slightly below the CSTV of 60 mg dm^{-3} but still slightly above the STP where response is not expected (Gatiboni et al., 2021).

At Rowan County, the average soybean yield in 2022 was 3470 kg ha^{-1} (USDA-NASS, 2023). In this study, the yield at ROW22 ranged from 4732 to 5347 kg ha^{-1} with an average of 4963 kg ha^{-1}. There was no statistically significant difference in yield between treatments. The initial STP was 139 mg dm^{-3} and no P fertilization would have been recommended per the NCDA&CS soil test report.

Figure 4. Average soybean yields in response to rates of phosphorus fertilizer at Union County in 2020 (UNI20), Beaufort County in 2020 (BEA20), Washington County in 2021 (WAS21), and Columbus County in 2021 (COL21)







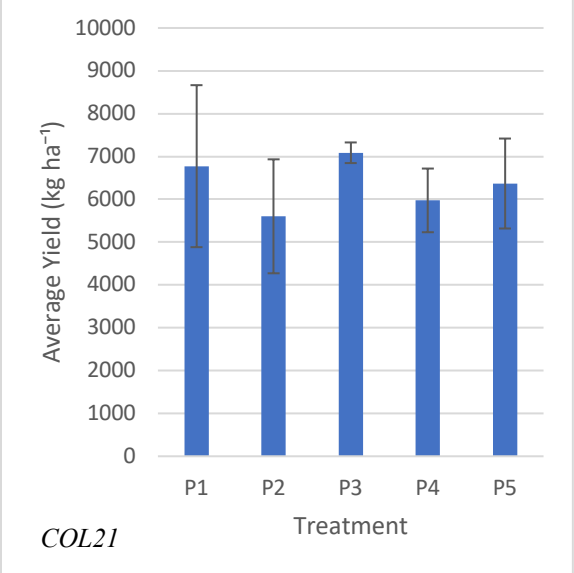
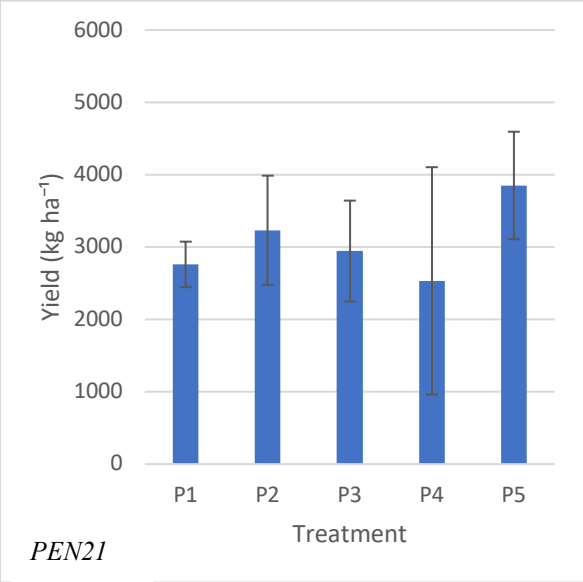
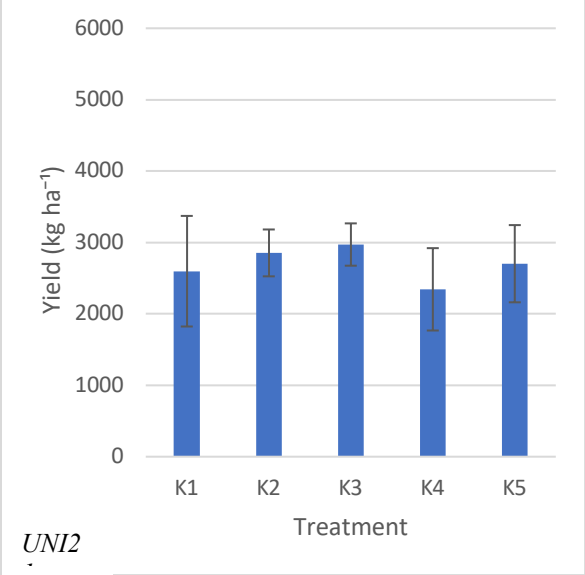
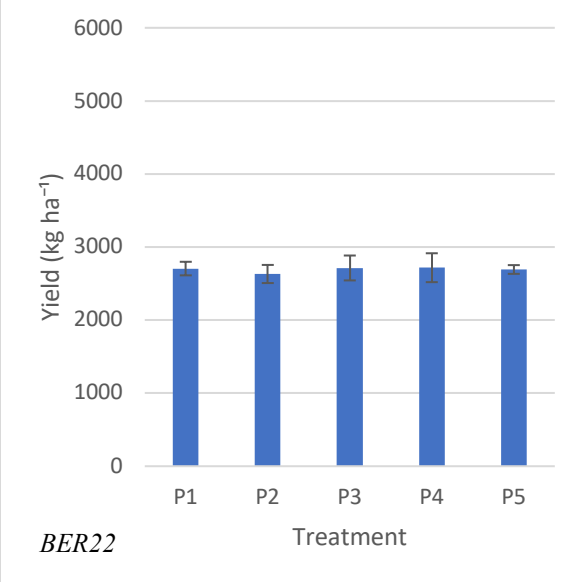
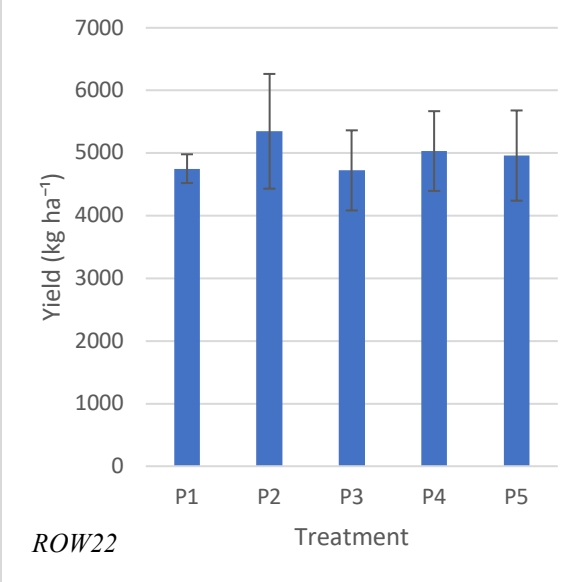


Figure 5. Average soybean yields in response to rates of Phosphorus fertilizer at Pender County in 2021 (PEN21), Union County in 2021 (UNI21), Bertie County in 2022 (BER22), and Rowan County in 2022 (COL22)









Yield Response to Potassium Rates

According to USDA NASS, the average soybean yield in Union County in 2020 was 3134 kg ha^{-1} (USDA-NASS, 2023). In our field in Union County (UNI20) yield ranged from 4146 to 4460 kg ha^{-1} with an average across all treatments of 4260 kg ha^{-1}. There was no statistically significant difference in yield between the five K treatments. Initial soil test data for UNI20 showed a K concentration of 80.5 mg dm^{-3}. The critical soil test value recommended by NCDA&CS is 98 mg dm^{-3} (Hardy et al., 2014). Morales et al. (2022) found inconsistent response to potassium fertilization in six site-years in North Carolina. Their results found CSTV of K ranging from 49 to 93 mg dm^{-3} in three site-years, while other three site-years with the same range of STK did not respond to K fertilization.

According to USDA NASS, the average soybean yield at Beaufort County in 2020 was 3201 kg ha^{-1} (USDA-NASS, 2023). Soybean yield at BEA20 ranged from 4386 to 5205 kg ha^{-1} and averaged 4646 kg ha^{-1} across all of the treatments. There was no significant difference in yield between any of the five treatments. BEA20 had an initial K concentration of 48 mg dm^{-3}, the lowest initial K concentration at any of the eight sites tested. Morales et al. (2021) tested rates of K in a Portsmouth soil in the Tidewater region and did not observe response to fertilization in a soil with 60 mg dm^{-3} of K, which is lower than the CSTV of 98 mg dm^{-3}.

According to USDA NASS, the average soybean yield at Columbus County in 2021 was 2387 kg ha^{-1} (USDA-NASS, 2023). The yield at COL21 ranged from 5975 to 7403 kg ha^{-1} and averaged 6673 kg ha^{-1} across all five treatments and no difference among the five treatments (Figure 6). COL21 had an initial K value of 118 mg dm^{-3}, meaning that no response was expected due to STK being higher than the CSTV. Note that the yield data was abnormally high at COL21 due to being hand harvested as a result of green stem disorder preventing combine

harvesting. Therefore, the yield at this site may not be accurate. The takeaway from COL21 is that there was no difference between K treatments and not the level of yield.

According to the USDA-NASS, the average soybean yield in Pender County in 2021 was 2871 kg ha^{-1} (USDA- NASS, 2023). PEN21 yield ranged from 2868 to 3625 kg ha^{-1} (Figure 7) and the average across all treatments was 3091 kg ha^{-1}. There was no significant difference in yield between the treatments. PEN21 was not considered a high yielding site as defined in this study of having a yield greater than 4000 kg ha^{-1}. This is due, in part, to PEN21 being a double cropped planning and therefore having a late planting date. Late season plantings tend to be smaller plants with less pods than a full season soybean plant. (Morris et al., 2021) PEN21 had an initial soil K value of 96 mg dm^{-3}.

UNI21 was the lowest yielding trial across all site years. The lower yields obtained in our study are a consequence of a late-season infestation of frogeye leaf spot disease. Yield ranged from 2344 to 2971 kg ha^{-1} and averaged 2694 kg ha^{-1} across all of the treatments. According to USDA-NASS, the average soybean yield in Union County in 2021 was 3060 kg ha^{-1}(USDA-NASS, 2023). Similar to other site years, there was no difference between treatments at UNI21. Initial soil K concentration was 88 mg dm^{-3}.

Yields in WAS21 ranged from 3988 to 4382 kg ha^{-1} and averaged 4173 kg ha^{-1} which is above the average of 3430 kg ha^{-1} estimated by the USDA-NASS for Washington County in 2021 (USDA-NASS, 2023) There was no statistically significant difference in yield between the treatments. WAS21 had an initial soil test concentration of 92 mg dm^{-3}.

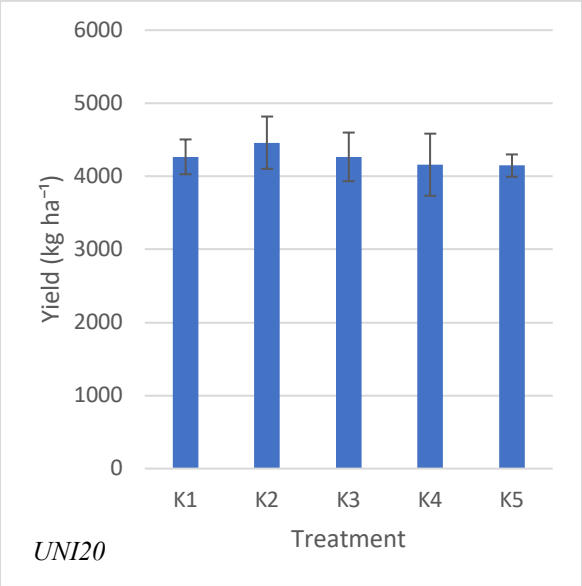
ROW22 yields ranged from 4923 to 5625 kg ha^{-1} and averaged 5139 kg ha^{-1}, this is above the USDA-NASS average yield of 3470 kg ha^{-1} for Rowan County in 2021 (USDA-NASS, 2023). There was no statistically significant difference in yield between the treatments. ROW22 had an

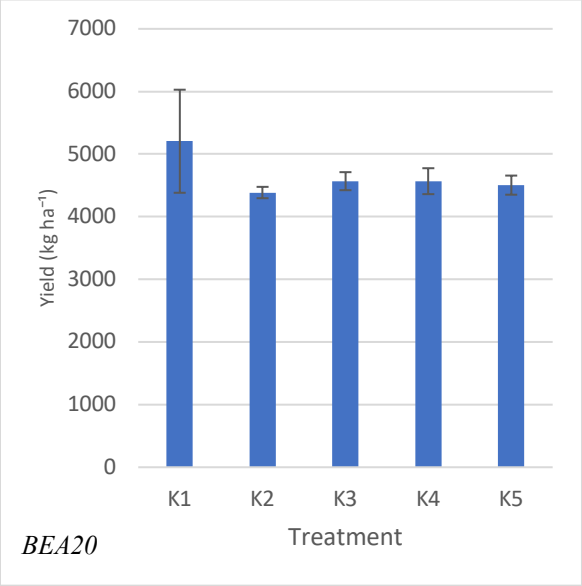
initial soil test K concentration of 156 mg dm^{-3}. This is the highest initial soil test K concentration out of any of the eight sites tested. Potassium fertilization would not be recommended in accordance with an NCDA&CS recommendations (Hardy et al, 2014).

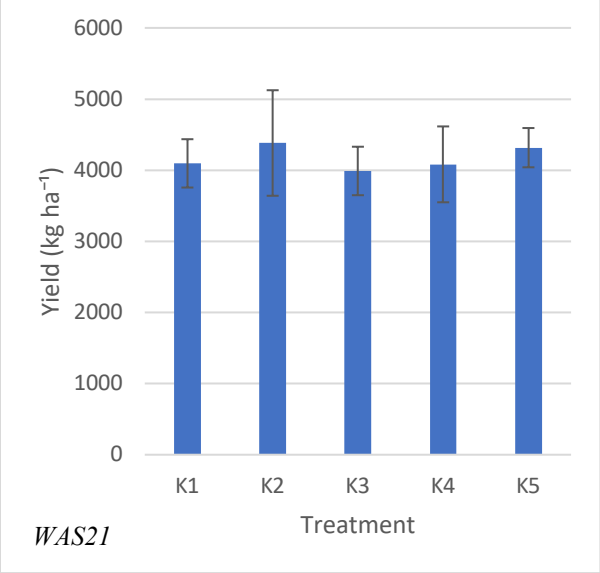
According to USDA-NASS, the average soybean yield at Bertie County in 2022 was 2475 kg ha^{-1} (USDA-NASS, 2023). BER22 yields ranged from 2571 to 2839 kg ha^{-1} and averaged 2729 kg ha^{-1} across all treatments. There was no response to treatments. Initial soil K was 101 mg dm^{-3} and no response to treatment was expected as the STK is over the CSTV of 98 mg dm^{-3}.

Overall, both the P and K concentrations in soil at all of the test sites were medium to high as determined by the initial soil tests. There were no statistically significant differences in yield between any of the P and K treatments. There were no results that indicated that increased K and P fertilization above a CSTV of 60 mg dm^{-3} for phosphorus and 98 mg dm^{-3} for potassium will positively impact yield, even in the high yielding environments tested in this study. This means that farmers can potentially increase profit through fertilizing in accordance with an annual soil test by avoiding over fertilization. Applying more fertilizer than needed increases costs through product used, additional time spent applying the treatments, wear and tear on machines, and fuel. Additionally, negative environmental impacts such as leaching and runoff can be avoided through only applying the necessary levels of fertilizer.

Figure 6. Average soybean yields in response to rates of potassium fertilizer at Union County in 2020 (UNI20), Beaufort County in 2020 (BEA20), Washington County in 2021 (WAS21), and Columbus County in 2021 (COL21)







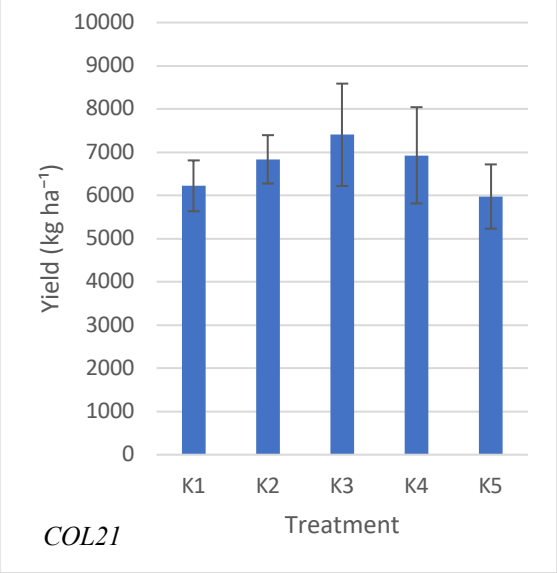
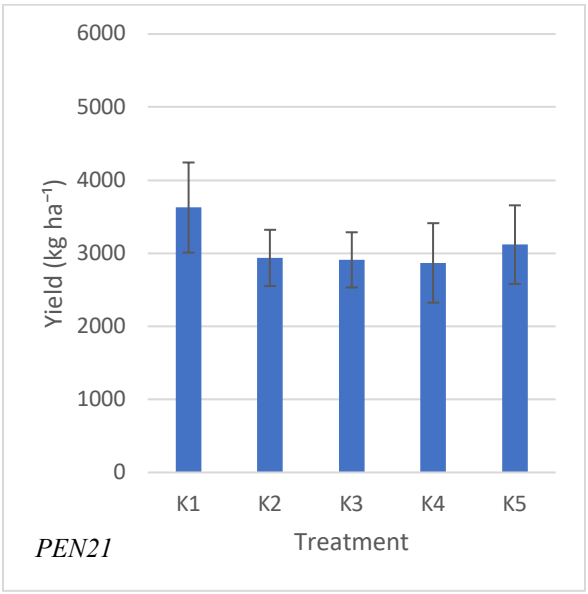
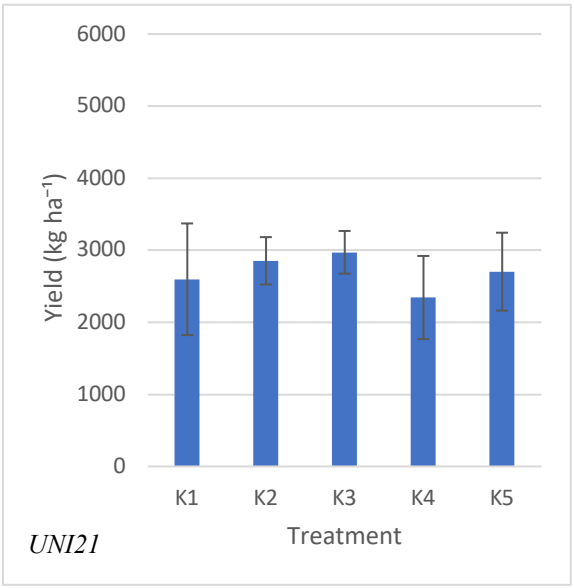
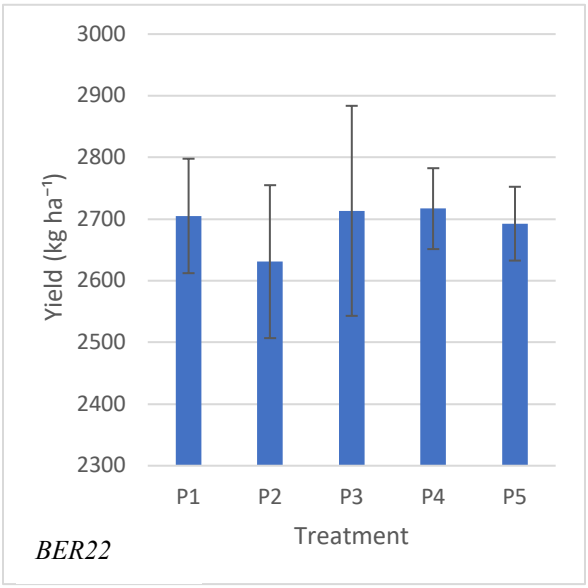
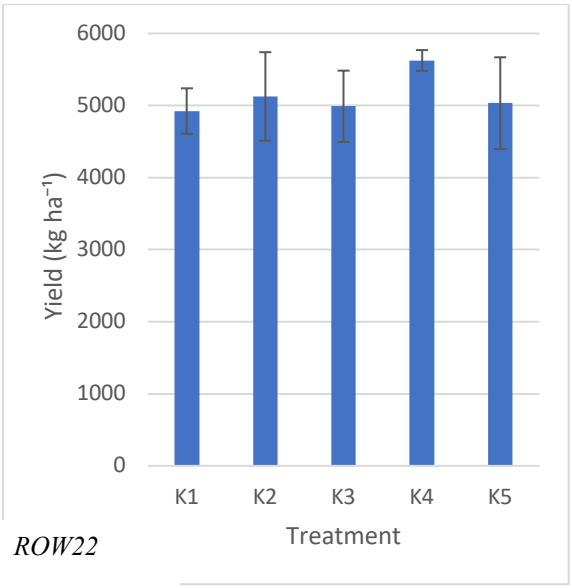


Figure 7. Average soybean yields in response to rates of potassium fertilizer at Pender County in 2021 (PEN21), Union County in 2021 (UNI21), Bertie County in 2022 (BER22), and Rowan County in 2022 (COL22)









Soil Response to Phosphorus Rates

Two sets of soil samples were collected during the study. The first was taken at planting to establish the baseline fertility (Table 4). The second was taken roughly a month after treatments were applied to gauge the amount of nutrients available to the plants as they were actively growing (Tables 6 and 7). In North Carolina, the general CSTV for P is currently established as 60 mg dm^{-3} (Hardy et al., 2014). Overall, nearly all of our sites had moderate to high levels of P in soil after treatment. Only two sites came in at or slightly below the CSTV, UNI20 and BER22.

At UNI20, P concentration in soil post fertilization ranged from 53.0 to 63.0 mg dm^{-3} and averaged 60.5 mg dm^{-3}. There was no statistical difference between samples and the average soil P was above the established CSTV of 60 mg dm^{-3}.

At BEA20, P rates ranged from 80.2 to 100 mg dm^{-3} and averaged 90 mg dm^{-3}. BEA20 did show statistical differences in P levels between the treatments, though they were all well above the CSTV of 60 mg dm^{-3}.

COL21 had P levels ranging from 74.7 to 95.5 mg dm^{-3} and averaging 84.0 mg dm^{-3}. There was no statistically significant difference in P levels between the treatments.

PEN21 had very high levels of P ranging from 166.2 to 199.7 mg dm^{-3} and averaging 174.4 mg dm^{-3}. There was no difference in the levels of P in soil between the treatments.

WAS21 had P levels ranging from 101.2 to 123.5 mg dm^{-3} and averaging 184.1 mg dm^{-3}. There was no statistical significance in P levels between treatments.

UNI21 had the highest levels of P out of any of the site-years. UNI21 ranged from 205.2 to 240.0 and averaged 226.9 mg dm^{-3}. There was no significant difference in soil P levels between treatments.

BER22 had the lowest soil P values post treatment out of any site-year. BER22 soil P ranged from 45.2 to 66.2 mg dm^{-3} and averaged 56.78 mg dm^{-3} which is slightly below the NCDA&CS CSTV of 60 mg dm^{-3}. There was a significant difference in levels of soil P between treatments.

ROW22 had P values ranging from 159.7 to 177.8 mg dm^{-3} and averaged 169.2 mg dm^{-3}. There was not a significant difference in levels of soil P at ROW22.

Table 6. Average phosphorus concentration in soil post treatment application at all site years

	UNI20	**BEA20**	**COL21**	**PEN21**	**WAS21**	**UNI21**	**BER22**	**ROW22**
	mg dm^{-3}							
P1	53.0	80.2 B	74.7	166.2	101.2	205.2	45.2 B	177.7
P2	62.7	90.2 AB	88.0	167.7	111.7	240.0	52.0 AB	166.5
P3	62.7	89.5 AB	81.5	192.7	121.2	222.5	59.0 AB	173.2
P4	61.0	100.0 A	80.5	199.7	113.0	233.0	66.2 A	159.7
P5	63.0	--	95.5	194.0	123.5	234.0	61.5 A	168.0
Average	60.5	90.0	84.0	174.7	184.1	226.9	56.78	169.2

*Different letters between treatments would indicate statistical differences at the 0.05 significance level.

Soil Response to Potassium Rates

Soil test potassium values at UNI20 ranged from 47.7 to 107.2 mg dm^{-3} and averaged 78.6 mg dm^{-3} (Table 7). This average is below the recommended CSTV of 98 mg dm^{-3}. There was a statistical difference in the levels of K in soil between treatments. UNI20 had the lowest K levels of any site-year.

BEA20 had K rates ranging from 80.5 to 113.2 mg $dm^{-3}$and averaging 96.4 mg dm^{-3} which is just slightly below the recommended CSTV of 98 mg dm^{-3}. There was a significant difference in K levels between treatments.

COL21 had K levels between 117.7 to 185.7 mg dm^{-3} and averaged 150.0 mg dm^{-3}. Again, there was a significant difference in the levels of K in soil between the treatments.

PEN21 had K rates ranging from 98.5 to 164.7 mg dm^{-3} and averaging 127.1 mg dm^{-3}. There was a significant difference in K levels in soil between treatments.

In WAS21 rates of K ranged from 92.2 to 225.0 mg dm^{-3} and averaged 167.6 mg dm^{-3}. As has been the trend, there was a statistical difference in levels of K between the different treatments.

At UNI21 rates of K in soil post treatment ranged from 88.0 to 136.0 mg dm^{-3} and averaged 117.0 mg dm^{-3}. There was a statistically significant difference in rates of K between the treatments.

Year 2022 was the only year we did not observe a difference in the levels of K between treatments. In BER22 K rates ranged from 76.2 to 151.5 mg dm^{-3} and averaged 113.0 mg dm^{-3}. In ROW22 rates of K ranged from 177.2 to 278.7 mg $dm^{-3}$and averaged 234.1 mg dm^{-3} and were the highest rates we saw at any site-year. Only two of the site-years had average K rates below the CSTV of 98 mg dm^{-3}, UNI20 and BEA20. The remainder of the site-years had moderate to high levels of K in soil post treatment.

Table 7. Average potassium concentration in soil post treatment application at all site years

	UNI20	**BEA20**	**COL21**	**PEN21**	**WAS21**	**UNI21**	**BER 22**	**RO W22**
	mg dm^{-3}							
K1	47.7 C	80.5 C	117.7 C	101.0 B	92.2 C	88.0 B	76.2	177.2
K2	67.7 BC	89.5 BC	125.0 BC	98.5 B	128.0 BC	108.0 AB	89.2	234.5
K3	85.7 AB	99.2 AB	165.5 A	137.2 AB	200.2 AB	134.5 A	133.0	197.0
K4	84.5 AB	99.5 AB	185.7 A	164.7 A	225.0 A	136.0 A	151.5	278.7
K5	107.2 A	113.2 A	156.0 AB	134.2 AB	192.5AB	118.5 AB	118.2	232.7
Average	78.6	96.4	150.0	127.1	167.6	117.0	113.0	234.1

*Different letters between treatments would indicate statistical differences at the 0.05 significance level.

Phosphorus Concentration in the Plant Tissue Analysis at Growth Stage R1

Phosphorus concentration was analyzed in the plant tissue ay R1 (beginning bloom) and the sufficiency range considered is 2.3 to 5.5 g kg^{-1} as recognized by the NCDA&CS (Hicks, 2023, personal communication).

Phosphorus at R1 in UNI20 ranged from 3.6 to 3.8 g kg^{-1} with an average of 3.7 g kg^{-1} (Table 8). In BEA20 P ranged from 3.8 to 4.0 g kg^{-1} with an average of 3.9 g kg^{-1}. P concentration in PEN21 ranged from 4.0 to 4.4 g kg^{-1} and averaged 4.2 g kg^{-1}. In WAS21 P concentration in tissue ranged from 2.8 to 3.1 g kg^{-1} and averaged 3.0 g kg^{-1}. WAS21 had the lowest P concentration of the five P treatments. In UNI21 P ranged from 4.2 to 4.4 g kg^{-1} and averaged 4.3 g kg^{-1}. UNI21 had the highest average P concentration in the tissue out of the five P treatments. BER22 ranged from 4.1 to 4.3 g kg^{-1} and averaged 4.2 g kg^{-1}. In ROW22 P values ranged from 3.8 to 4.1 g kg^{-1} and averaged 3.9 g kg^{-1}. In COL21 P ranged from 3.6 to 4.0 g kg^{-1} with an average of 3.82 g kg^{-1}. COL21 was the only site that presented a statistically significant difference in P concentration between the five P treatments, however the increase in P in the plant tissue did not follow the rates of P fertilizer applied.

The P concentration in the plant tissue in all sites were within the sufficiency range for soybean plants at R1, indicating that all sites there was adequate phosphorus nutrition, regardless of the rate of P fertilizer applied (Table 8).

The sufficiency range utilized by NCDA (2.3 to 5.5 g kg^{-1}) to indicate a proper concentration of P in soybean tissue at R1 is similar on the high end but a bit lower on the low end to ranges noted by other research. Mallarino (2019) notes a P sufficiency range of 3.5 to 4.2 g kg^{-1}. Blessitt (2020) reported a narrower sufficiency range than most, hovering near the high end of other reported sufficiency ranges recommending 4.8 to 5.4 g kg^{-1}. The Southern

Association of Agriculture Experiment Station Directors (AAESD) indicates that the proper P sufficiency range at flowering would be 3.0 to 6.0 g kg^{-1} with a critical value of 3.0 g kg^{-1} (Sabbe et al., 2011). These other findings could indicate that the NCDA&CS's sufficiency range for P is too wide and that the low end needs to be increased. Aside from UNI21, all of our results were above the CV noted by AAESD and fell within their listed sufficiency range. Outside of UNI21 the lowest sufficiency range from our experiment was 3.6 g kg^{-1}.

Table 8. Average phosphorus concentration in soybean tissue at growth stage R1 at all site years

	UNI20	**BEA20**	**COL21**	**PEN21**	**WAS21**	**UNI21**	**BER22**	**ROW22**
	g kg^{-1}							
P1	3.8	3.8	3.8 AB	4.1	2.9	4.3	4.1	4.1
P2	3.7	4.0	3.6 B	4.3	2.9	4.2	4.1	3.8
P3	3.7	3.9	3.8 AB	4.1	3.1	4.3	4.3	4.0
P4	3.6	4.0	4.0 A	4.0	3.1	4.4	4.3	4.0
P5	3.7	--	4.0 A	4.4	3.0	4.4	4.3	3.8
Average	3.7	3.9	3.9	4.2	3.0	4.3	4.2	3.9

Potassium Concentration in the Plant Tissue Analysis at Growth Stage R1

Potassium concentration was analyzed in tissue at R1 (beginning bloom) and the sufficiency range is 17.6 to 28.0 g kg^{-1} as recognized by the NCDA&CS (Hicks, 2023, personal communication).

In UNI20 K ranged from 24.2 to 27.6 g kg^{-1} and averaged 25.4 g kg^{-1} (Table 9). BEA20 had a range of K concentrations from 21.6 to 27.5 g kg^{-1} with an average K concentration of 24.8 g kg^{-1}. BEA21 did show a statistically significant difference in K concentration between the five treatments. The site-year, COL21 had a K range of 18.0 to 19.3 g kg^{-1} with an average of 18.8 g kg^{-1}. COL21 also showed a statistically significant difference in K concentration between treatments. Additionally, COL21 had the lowest average K concentration across treatments in tissue at R1. PEN21 K concentration in tissue ranged from 20.6 to 21.9 g kg^{-1} with an average of

21.2 g kg^{-1}. WAS21 had the highest average K concentration in tissue at R1 across all treatments.WAS21 R1 tissue K concentrations ranged from 35.0 to 38.7 g kg^{-1} and averaged 37.2 g kg^{-1}. WAS21 also noted significant differences in K concentration between the five treatments. UNI21 K concentration in tissue at R1 ranged from 19.9 to 22.4 g kg^{-1} and averaged 21.4 g kg^{-1}. BER22 K concentration ranged from 18.4 to 18.9 g kg^{-1} and averaged 18.9 g kg^{-1}. Finally, K concentration in ROW22 ranged from 19.8 to 21.2 g kg^{-1} and averaged 20.7 g kg^{-1}.

The K concentrations observed in the tissue analysis at R1 were all within the sufficient range recommended by the NCDA&CS with the exception of WAS21 where all of the treatments had higher K concentration that sufficient, being classified as “high”. The excess K seen in the UNI21 samples are an example of luxury consumption when the soybean plants were taking up excess K as it was available, it did not lead to an increase in final yields. The same phenomena was observed by Morales et al. (2022).

In general, the K sufficiency range recommended by the NCDA&CS (17.6 to 28.0 g kg^{-1}) is in line with the sufficiency range found in other studies. Blessitt (2020) recommended a higher and more narrow range than most literature advising a sufficiency range of 23.3 to 25.4 g kg^{-1}. Mallarino (2019) recommended a sufficiency range of 18.0 to 25.0 g kg^{-1}. The AAESD recommends a K sufficiency range of 15.0 to 22.5 g kg^{-1} with a critical value of 15.0 g kg^{-1} (Sabbe et al., 2011). The NCDA&CS recommendations are within or close to the ranges recommended by the other studies on the low end and are a bit higher than the recommendations on the high end. This ensures that the plants have an adequate amount of K (15 g kg^{-1}) at beginning flowering (Sabbe et al., 2020).

Table 9. Average potassium concentration in soybean tissue at growth stage R1 at all site years

	UNI20	BEA20	COL21	PEN21	WAS21	UNI21	BER22	ROW22
	g kg^{-1}							
K1	24.7	21.6 C	19.2 A	21.2	35.0	19.9 B	18.4	19.8
K2	27.6	22.7 BC	18.0 B	21.3	37.7	21.1 AB	18.6	20.7
K3	25.2	25.6 AB	18.8 AB	21.9	38.2	22.1 A	18.8	20.8
K4	25.2	26.4 A	19.0 AB	20.9	38.7	22.4 A	18.9	20.9
K5	24.2	27.5 A	19.3 A	20.6	36.4	21.3 AB	19.9	21.2
Average	25.4	24.8	19.0	21.2	37.2	21.4	18.9	20.7

Nutrient Concentration in Grain and Nutrient Exports

Following harvest, we analyzed the grain for in all site-years to assess the concentration of P and K present in the grain to calculate the amount of P and K exported with the grain. In UNI20 the P concentration in grain post-harvest ranged from 4.9 to 6.2 g kg^{-1} and averaged 5.7 g kg^{-1} (Table 10). In UNI20, there were statistically significant differences in the concentration of P between the five treatments. In BEA20 the P concentration ranged from 6.3 to 6.4 g kg^{-1} and averaged 6.3 g kg^{-1}. In BEA20 there was a statistically significant difference in P concentration in grain between the five treatments. There were no differences in grain nutrient concentration in the remaining sites (Table 10). In COL21 the concentration of P present in the grain sample ranged from 6.0 to 6.3 g kg^{-1} and averaged 6.2 g kg^{-1}. In PEN21 the P concentration in grain ranged from 5.9 to 6.2 g kg^{-1} and averaged 6.0 g kg^{-1}. In WAS21 P concentration ranged from 4.6 to 4.9 g kg^{-1} and averaged 4.7 g kg^{-1}. UNI21 had P concentrations ranging from 6.7 to 6.8 g kg^{-1} and averaged 6.7 g kg^{-1}. UNI21 had the highest concentration of P in the grain out of any of the five P treatments. BER22 had P concentrations in grain ranging from 4.0 to 4.1 g kg^{-1} and averaged 4.0 g kg^{-1}. BER22 had the lowest averaged P concentration out of the five P treatments. P concentration in grain at ROW22 ranged from 5.0 to 5.1 g kg^{-1} and averaged 5.0 g kg^{-1}. Recent literature recognized that average removal of P by soybean is between 4.9 to 5.5 g

kg^{-1} (Neto et al., 2021; Filippi et al., 2021). With the exception of ROW22 and UNI22 all of the site-years tested averaged at (BER22) or above (UNI20, BEA20, COL21, PEN21, WAS21) the reported average.

Table 10. Average phosphorus concentration in soybean grain, post-harvest, at all site-years

	UNI20	**BEA20**	**COL21**	**PEN21**	**WAS21**	**UNI21**	**BER22**	**ROW22**
	g kg^{-1}							
P1	4.9 B	6.2	6.0	5.9	4.6	6.9	4.1	5.0
P2	5.6 A	6.3	6.1	6.0	4.7	6.7	4.1	5.1
P3	5.8 A	6.4	6.2	6.2	4.7	6.7	4.0	5.0
P4	5.9 A	6.4	6.2	6.0	4.9	6.7	4.0	5.1
P5	6.2 A	--	6.3	6.2	4.8	6.8	4.0	5.0
Average	5.7	6.3	6.2	6.1	4.7	6.8	4.0	5.0

In the UNI20 site, K concentration ranged from 18.6 to 19.6 g kg^{-1} and averaged 19.1 g kg^{-1} (Table 11). BEA20 presented K concentrations ranging from 20.6 to 22.3 g kg^{-1} and averaging 21.6 g kg^{-1}. UNI20 had statistically significant differences of the K concentration in grain between treatments. COL21 had K concentrations in the grain that ranged from 15.7 to 16.2 g kg^{-1} and averaged 15.9 g kg^{-1} across all treatments. COL21 had the lowest K concentration in grain across all treatments. In PEN21, K concentrations ranged from 17.5 to 18.0 g kg^{-1} and averaged 17.8 g kg^{-1} across all treatments. The K concentration in WAS21 ranged from 19.1 to 21.1 g kg^{-1} and averaged 20.5 g kg^{-1}. In UNI21 average K concentration in grain ranged from 21.1 to 22.1g kg^{-1} and averaged 21.5 g kg^{-1}. BER22 had the highest K concentration in grain out of all eight sites. In BER22 K concentration in grain ranged from 21.6 to 23.2 g kg^{-1} and averaged 22.4 g kg^{-1}. Finally, in ROW22 K concentration ranged from 18.0 to 18.5 g kg^{-1} and averaged 18.1 g kg^{-1}. FIlippi et al. (2021) recognized the average concentration of K in grain to be 16.8 g kg^{-1}. With the exception of COL21 all site-years averaged above the average concentration reported by

Filippi et al. (2021).The higher-than-average concentrations of P and K in grain may be a result of luxury consumption by the plants due to excess nutrients in the soil.

Table 11. Average potassium concentration in soybean grain, post-harvest, at all site-years

	UNI20	**BEA20**	**COL21**	**PEN21**	**WAS21**	**UNI21**	**BER22**	**ROW22**
	g kg^{-1}							
K1	18.6	20.6 C	15.7	17.7	19.1 B	21.2	21.8	18.0
K2	19.6	21.1 BC	16.0	17.5	20.3 AB	21.1	21.6	18.5
K3	19.4	21.8 ABC	16.0	17.9	21.1 A	21.4	23.2	18.2
K4	19.1	22.6 AB	16.2	17.8	21.0 AB	21.9	23.2	18.0
K5	19.0	23.4 A	15.9	18.1	19.5 AB	22.1	22.2	18.0
Average	19.14	21.9	16.0	17.8	20.18	21.5	22.4	18.1

Finally, we examined the export of P and K from each site. In general, this will trend the same as the yield. In UNI20 export of P ranged from 19.8 to 26.7 kg ha^{-1} and averaged 24.0 kg ha^{-1} (Table 12). There was a statistically significant difference in the amount of P exported between the P treatments only at this location. In BEA20 amounts of P exported ranged from 25.4 to 27.3 kg ha^{-1} and averaged 26.2 kg ha^{-1}. In COL21, P export ranged from 33.2 to 43.2 kg ha^{-1} and averaged 39.0 kg ha^{-1}. However, it is important to highlight that this site was hand-harvested and the yield was based only on the measurement of ten plants. PEN21 saw P exports ranging from 14.9 to 23.8 kg ha^{-1} and averaging 18.4 kg ha^{-1} across all five treatments. In WAS21, P export ranged from 18.9 to 22.1 kg ha^{-1} and averaged 20.6 kg ha^{-1}. In UNI21 exports range from 17.2 to 18.6 kg ha^{-1} and average 18.0 kg ha^{-1}. In BER22 export of P ranged from 11 to 11.1 kg ha^{-1} and averaged 11.0 kg ha^{-1}. This was the lowest export of P from all of the eight sites. Finally, in ROW22 P export ranged from 23.5 to 27.0 kg ha^{-1} and averaged 25.1 kg ha^{-1}.

Table 12 show a range of P export from 11 to 47.4 kg ha^{-1} and average of 22.7 kg ha^{-1} of P. Using the conversion factor of 2.29, it represents 25 to 109 kg ha^{-1} of P_2O_5 and an average of 52 kg ha^{-1} of P_2O_5.

Bender et. al (2015) found P exports on fertilized land to be on average 18.0 kg ha^{-1} with a yield of 3480 kg ha^{-1}. Similarly, Osmond and Kang (2008) reported P exports of 19.6 kg ha^{-1} with a yield of 3480 kg ha^{-1}. Our study found exports between 18.0-26.2 kg ha^{-1}, except for COL21. This would indicate that we are exporting more P than other studies due to the excess fertilization. The increased export is not tied to the increased rates of P and K that we applied. Instead, it is due to the general good fertility present in the soil.

Table 12. Average phosphorus export in response to phosphorus treatments, at all site-years

	UNI20	**BEA20**	**COL21**	**PEN21**	**WAS21**	**UNI21**	**BER22**	**ROW22**
	kg ha^{-1}							
P1	19.8 C	25.4	41.2	16.3	21.6	18.0	11.0	23.9
P2	23.5 B	26.8	33.2	19.0	18.9	18.6	10.6	27.0
P3	25.3 AB	25.5	43.2	18.0	20.2	18.0	11.0	23.5
P4	24.5 AB	27.3	37.4	14.9	21.2	18.1	11.0	25.4
P5	26.7 A	--	40.1	23.8	22.1	17.2	11.1	25.4
Average	24.0	26.2	39.0	18.4	20.6	18.0	11.0	25.1

There was no differences in K export within a location due to K rate (Table 13). In UNI20 export of K ranged from 79.0 to 87.4 kg ha^{-1} and averaged 81.5 kg ha^{-1} (Table 11). BEA20 presented exports ranging from 92.6 to 103.1 kg ha^{-1} and averaged 99.4 kg ha^{-1}. In COL21 exports of K ranged from 94.0 to 119.1 kg ha^{-1} and averaged 106.4 kg ha^{-1} across all treatments. In PEN21 K exports ranged from 51.0 to 64.1 kg ha^{-1} and averaged 54.9 kg ha^{-1} across all five treatments. PEN21 was our lowest K exporting site out of all eight sites. In UNI21, K exports ranged from 51.1 to 65.6 kg ha^{-1} and averaged 58 kg ha^{-1}. Moving into 2022, BER22 ranged from 59.2- 66.0 kg ha^{-1} and averaged 61.2 kg ha^{-1}. ROW22 K exports ranged from 86.6-101.1 kg ha^{-1} and averaged 92.4 kg ha^{-1}. WAS21 K exports ranged from 64.6 to 89.3 kg ha^{-1} and averaged 80.5 kg ha^{-1}.

Table 13 show a range of K export from 51.1 to 119.1 kg ha^{-1} and average of 79.6 kg ha^{-1} of K. Using the conversion factor of 1.20, it represents 61 to 143 kg ha^{-1} of K_2O and an average of 96 kg ha^{-1} of K_2O.

Kang and Osmond (2008) estimated K exports to be 69.5 kg ha^{-1} in a site yielding 3362.6 kg ha^{-1}. Bender et al. (2015) noted a K export of 66 kg ha^{-1} in a site yielding 3480 kg ha^{-1}. Our range of 51.1 to 119.1 kg ha^{-1} is a bit on the high end but, the COL21 site may be overestimated. Four of our sites exported no less than 78 kg ha^{-1}. Again, these high exports are due to luxury uptake by the plants. From a profit standpoint, this is undesirable. The producer is spending more money on fertilizer and seeing no benefit in terms of yield and therefore profit.

Table 13. Average potassium export in response to potassium treatments, at all site-years

	UNI20	**BEA20**	**COL21**	**PEN21**	**WAS21**	**UNI21**	**BER22**	**ROW22**
	kg ha^{-1}							
K1	79.0	99.7	97.7	64.1	78.1	55.5	59.2	86.6
K2	87.4	92.6	109.0	51.2	89.3	60.1	60.5	94.7
K3	82.9	101.1	119.1	52.0	64.6	65.6	60.0	89.2
K4	79.3	103.2	112.0	51.1	86.4	51.1	66.0	101.1
K5	78.8	101.0	95.0	56.2	84.1	60.0	60.1	90.4
Average	81.5	99.4	106.4	54.9	80.5	58.4	61.2	92.4

In summary, this study was conducted over eight site years in the Coastal Plain and Piedmont regions of North Carolina. Each of these sites started with moderate to very high phosphorus and potassium availability. We tested five different rates of potassium and five different rates of phosphorus and replicated those treatments four times at each site. Because the sites all had close to the NCDA&CS CSTV, there was no yield response to fertilization. This indicates that the recommended CSTVs are sufficient even in high yielding soybean environments. Fertilization above the CSTV is not advised as it can hurt profitability and harm the environment. When there are excess nutrients the soybean plant will uptake and export the

excess nutrients. This removes extra nutrients from the soil requiring more to be added next season without seeing the benefit of a higher yield, if the farmer intends to keep the same level of K. When nutrient analysis was performed on the soybean tissue at R1 (beginning flower) as well as on the grain following harvest, we generally did not see a difference in P and K between the treatments. We did see overall higher levels of P and K in the grain and somewhat higher levels in the tissue in comparison to data from literature. This is due to there being a concentration of nutrient above the required, regardless of treatments. The exports we reported are proportional to the yield at each site-year. If we are following the sufficiency fertilization philosophy, the rates of P and K will decrease as we move towards CSTV, and then will level off. Continuing to add nutrients above that point will not translate into higher yielding soybeans. Fertilization based on the NCDA&CS recommendations will provide fertilizer rates that optimize yield while also maximizing profit. If there are high reserves of P and K in soil from years of over fertilization then no additional fertilization would be required. Annual or bi-annual soil tests are recommended and eventually, as nutrient levels decrease due to crop nutrient removal, P and K fertilization would again be recommended.

Conclusion

Higher rates of P and K are not needed in high-yielding (>4000 kg ha^{-1}) soybean fields as long as they have a soil test value above the CSTV of 60 mg kg^{-1} of P and 98 mg kg^{-1} of K recommended by NCDA&CS. In general, fertilization increased the soil testing values, especially K, but these nutrients did not increase consistently in the plant tissue at R1 growth stage. The amount of P and K exported by grain was greater than reported in the literature, indicating the exports of nutrients are higher in high-fertility fields. The current

recommendations are adequate for high-yielding environments and it is not necessary to recommend more nutrients to high-yielding environments if the P and K are above the CSTV.

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