Full-Season and Double-Crop Soybean Response to Potassium Fertilizer

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ABSTRACT

Demand for potassium (K) increases with increasing soybean yield. Little research has been conducted on soybean response to K on coastal plain and piedmont soils of Virginia, especially in double-crop systems. Nineteen full-season and 14 double-crop soybean experiments were conducted in 2013 and 2014 in Virginia and northeastern North Carolina to determine full-season and double-crop soybean (with wheat straw remaining or removed) response to soil test K and K fertilizer application rates. Field moist, air dried, and oven dry soil test K extraction techniques were also compared to predict responsiveness of sites to K applications. Potassium fertilizer increased yield in five of 19 full-season experiments and one of 14 double-crop experiments. Full-season soybean yield plateaued at 88% relative yield and soil test K value of 38.8 mg K kg^{-1}. Full-season plant K critical concentrations were 18.2 g K kg^{-1} for V5 and 24.6 g K kg^{-1} for R2. Although critical concentrations could not be determined for double-crop soybean, V5 and R2 concentrations ranged from 17.6 to 35.6 g K kg^{-1} or 13.2 to 28.1 K kg^{-1}, respectively, most of which were within or above accepted sufficiency levels. Eight of 13 sites resulted in greater soil K concentrations when alternative soil drying methods were compared to air-dry methods. However, differences were not consistent and no single method was superior for these soils. More data is needed for double-crop soybean systems due to lack of response and lack of low soil test K sites in these experiments.

Dedication

I would like dedicate this thesis to four of the most important men in my life: my fiancé Jordan, my Daddy, my Umpa, and my Uncle Phil. You each have a very special place in my heart and without your constant encouragement and inspiration, I could not have made it. Thank you for pushing me to finish graduate school and telling me the truth when I needed to hear it, even when I did not want to. And special thanks to Jordan, for our after midnight talks when I couldn't sleep and our early morning talks while I was on the way to my research plots. I cannot wait for the rest of our lives together!

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Chapter 1 – Introduction and Justification

Soybean [*Glycine max* (L.) Merr.] production systems in the Mid-Atlantic, U.S.A. include full-season (April or May planted) or double-crop (June or July planted; following small grain harvest). Double-crop systems are often more profitable on a hectare basis than monoculture soybean systems because they allow two crops to be grown and harvested in a single year (Farno et al., 2002). Farmers in the Mid-Atlantic harvested 1,314,419 hectares of soybean in 2013, 42% of which were double-crop (NASS, 2015). Five-year average yield for full-season and double-crop soybean in the Mid-Atlantic was 2,620 kg ha^{-1}, compared to a five-year average yield of 1,400 kg ha^{-1} in 1965 and an average of 112,859 hectares of soybean harvested from 1961 to 1965. Soybean production and yield have nearly doubled in the past 50 years and current Virginia Cooperative Extension recommendations for potassium (K) fertilizer may also need to be increased for soybean in order to keep up with increased yield and increased nutrient demand.

With the double-crop system, straw remaining from small grain harvest may be left on the field or harvested for additional uses. Wheat straw provides ground cover that can hold topsoil in place and limits runoff of soil, chemicals and fertilizer to surface water. In addition, straw left on the ground can be decomposed into soil organic material and release nutrients to the succeeding soybean crop. However, some farmers remove the straw after the small grain is harvested, and thereby remove nutrients that would have been returned to the soil. The contribution of wheat straw to soil organic matter and nutrient content and the effects of straw harvest and retention have on soybean yield is unclear and needs further study.

Potassium is a vital soil nutrient for soybean and required in the second greatest amount, following nitrogen. Being a structural component of soil minerals, K is not always in a plant available form. Potassium is present in the mineral form (90-98 % soil K), slowly available form (1-10 % soil K) and exchangeable and solution form (0.1-2 % soil K). Therefore, regular K fertilization is necessary to prevent nutrient deficiencies in the soil because soils are often unable to supply the K necessary for high yielding crops. Still, there is a continuous cycle of K from primary materials to slowly available and exchangeable forms (Havlin et al., 2005). Over time, unharvested plant residue can degrade and return nutrients to the soil. Soil nutrient levels will increase if nutrient applications exceed the crop removal.

Potassium fertilizer is typically applied as a broadcast granular blend using muriate of potash. In some cases, it is applied in a band near the seed. Buah et al. (2000) found that surface broadcast K fertilization is equal or superior to subsurface band placement. Surface fertilizer application is therefore a method of preference. Varied responses to broadcast fertilizer were observed based on initial soil K concentration. Soils with lower K concentration had greater increase of K concentration after broadcast application whereas medium and high K testing soils were had little to no increase in soil K concentration (Yin and Vyn, 2003).

Soil testing is an important aspect of plant nutrient management and can help determine soil K levels. However, Yin and Vyn (2003), Fernandez et al., (2008) and Evanylo (1991) sampled soil K at multiple layers and found that soil in the surface 0-5 cm has significantly greater K concentration than that at 10-20 cm. Soybean roots can reach depths greater than the average sampling depth (0 to 15 cm) for row crops and it may be necessary to determine the concentration of K throughout the whole root region in order to know the total exchangeable K available for plant uptake.

Attoe and Truog (1946), showed the relation of K fertilizer needed to the remaining amount exchangeable K is log Y = k log X + c, where Y is amount exchangeable K, X is application rate, and k and c are constants determined by extent of fixation. However, research performed by Iowa State University during the 1960s and 1970s found that testing field-moist (not dried) soil samples gave a better estimate of K. Drying soils increased K concentrations, leading to lower than necessary K fertilizer recommendations (Mallarino, 2012). Grava et al (1961) determined that both air and oven dry samples have increased exchangeable K compared to field moist samples. When K fertilizer was applied at rates of 0, 269 and 538 kg K_2O ha^{-1}, average exchangeable K content were 36.5, 31.0 and 14.2 g K kg^{-1}greater than field moist soils, respectively, after air drying and 55.1, 42.9 and 23.7 g K kg^{-1}greater than field moist soils, respectively, after oven drying than. Low K testing soils will generally lead to a greater difference between field moist and dry soil analysis (Grava et al., 1961).

Potassium is one of the most abundant cations in plants and is associated with many physiological processes supporting growth and development (Fagaria, 2009; Havlin et al., 2004; Shingles and McCarty, 1994; Talbott et al., 1998; Tiwari, 2001). Potassium is mainly found in the cytoplasm and cell vacuole where K regulates stomatal functions, activates enzymes, and maintains osmotic balance. Potassium also plays a vital role in photosynthesis and supports sink tissues and transport of nutrients throughout the plant. Potassium ions aid photosynthesis by maintaining charge balance at the site of ATP production. Potassium deficient plants have a reduced rate of ATP production, which leads to increased respiration and slower growth and development (Fagaria, 2009; Havlin et al., 2004). Lower available K levels can lead to a reduction in the number of leaves produced as well as a reduction in the size of the leaves and the amount of canopy closure. Reduced leaf area causes less sunlight interception; which leads to reduced photosynthetic activity and an overall yield reduction (Tiwari, 2001). However, canopy closure and reduction of sunlight interception is dependent upon row spacing of soybean plants.

In addition to photosynthesis, inadequate K can reduce plant protein metabolism. Potassium has a beneficial effect on symbiotic N_2 fixation by affecting the number, fresh weight, and size of nodules or by affecting the amount of nitrogen fixed per unit time and mass of the nodule (Munson, 1985; Fagaria, 2009). The authors also stated that soybean plants that are well supplied with K produce more dry matter and are capable of accumulating more nitrogen. Soybean plants that receive sufficient K are able to synthesize more carbohydrates and eventually accumulate more N. Potassium deficient soybeans are also susceptible to pod and stem blight caused by [*Diaporthesojae L.*] Higher rates of K may decrease disease incidence in some crops. Potassium deficiency symptoms in soybeans include chlorosis and necrosis of leaf edges. Because K is mobile, deficiency symptoms first appear in lower leaves and move toward the top of the plant (Munson, 1985; Fagaria, 2009).

In Arkansas, a study consisting of 34 site-years was conducted on silt loam soils that ranged from 46 to 167 mg Mehlich-3 extractable K kg^{-1} (Slaton et al., 2010). Soybean responded positively to K applications (applied at 0 to 148 kg K ha^{-1}) to all sites where Mehlich-3-extractable K was less than 91 mg K kg^{-1} and nine of 15 sites where extractable K ranged from 91 to 130 K kg^{-1}. According to a study by Clover and Mallarino (2012) in Iowa, potassium fertilization increased soybean yields when applied at 71 to 117 kg K ha^{-1} at four of ten sites. On average, soybean responded linearly to K rate up to 103 kg K ha^{-1}. Soybean also responded to K applied to corn in the previous growing season at 3 of 10 sites, where the linear yield response continued up to 168 kg K ha^{-1}, which was the greatest K rate used.

An Ontario study comparing three fertilizer placement methods, two conservation tillage systems, and two soybean row widths found that critical leaf K concentration for maximum seed yield of conservation-till soybean was determined to be approximately 24.3 g kg^{-1} (Yin and Vyn, 2004). Clover and Mallarino (2012) determined that critical leaf K concentration for soybean was 17.6 to 20.0 g K kg^{-1} for maximum yield. In comparison, current Virginia Cooperative Extension recommendations suggests a leaf K sufficiency range between 17.5 and 25 g K kg^{-1} (Donahue, 2000)

Plant tissue sampling during the growing season may be used to determine at which periods of growth and development nutrients are utilized. It can also be used to diagnose in-season nutrient deficiencies. Potassium applications of 100 kg K ha^{-1}, applied as potassium chloride, KCl, increased soybean leaf K concentrations by 5.1 to 8.0 g kg^{-1} (Yin and Vyn, 2004). Coale and Grove (1991) determined K content using atomic absorption spectrometry of whole soybean plants at R1 (first flower), R5 (0.3 cm seed in top four nodes), and R7 (one mature pod on the plant) (Fehr and Caviness, 1971). Total accumulation of potassium under high K fertility (88+ mg K kg^{-1}) was increased by 87, 144, and 125 % at R1, R5, and R7, respectively. Total dry matter was not affected by K fertility and it is thought that total K accumulation was due to differences in K tissue concentration.

Potassium concentration can also affect the seed components, including oil, protein and starch. Seed composition can be affected by fertilizer rates, which ultimately affect germination and vigor. Yin and Vyn (2003) determined that seed K concentration levels increased from 1.3 to 2.7 g kg^{-1} with K fertilizer application. The data suggested that higher seed K concentrations might have significant influence on other seed attributes since K is widely involved in plant metabolic activities as an enzyme activator.

The 4R's of plant nutrition, developed by the International Plant Nutrition Institute, represent a holistic approach to fertilizer management practices. The 4R's include: right source, right rate, right time, and right place (IFA Task Force, 2009). The framework shows how achieving social, economic, and environmental goals can be managed by proper fertilization. It is important to utilize the 4R's when making recommendations for fertilizer. Right source represents correct rates of fertilizer and balanced nutrient management plans. Right rate of fertilizer can be ensured by soil testing, understanding crop nutrient removal, and plant tissue analysis. Right time and right place ensure crop nutrient uptake is optimal and plant injury is limited. It is important to apply site-specific rates of K based on changes in K levels between or within fields; therefore, enhancing productivity and environmental quality on the farm, landscape, and ecosystem. Proper rate of application prevents excess buildup of nutrients as well as less runoff of fertilizer into water systems which help enhance environmental quality.

The importance of potassium in soybean fertilization is made obvious by previous research results. Potassium fertilization of soybean increased K content in the plant and improved metabolic and photosynthetic processes. Although there has been significant research performed in Iowa, Arkansas, and the Mid-West, research applicable to the Mid-Atlantic is lacking. Research pertinent to the Mid-Atlantic region would influence whether or not current K fertilizer recommendations for full-season and double-crop soybeans need adjustment. The objective of this study was to determine full-season yield response to soil test K and K fertilizer application rates on Coastal Plain and Piedmont soils of Virginia and northeast North Carolina.

Objectives

1. Determine full-season and double-crop soybean (with straw remaining or removed) response to soil test K and K fertilizer rates on Coastal Plain and Piedmont soils of Virginia and North Carolina.

   Specifically:

   a. Correlate relative yield, V5-stage plant K concentration, and R2-stage trifoliate leaf K concentration with Mehlich-1 extractable soil K.
   b. Establish critical tissue K concentrations for V5 and R2-stage soybean.
   c. Quantify the K fertilizer rates required to maximize soybean yield at various soil test K levels.

2. Determine if moist soil analysis provides better relationship with soil test K levels when compared to air and oven-dry soil analysis.

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Chapter 2 – Full-Season Soybean Response to Potassium on Coastal Plain and Piedmont Soils of Virginia

ABSTRACT

Adequate potassium (K) nutrition is vital to high-yielding soybean [*Glycine max* (L.) Merr.] on Piedmont and Coastal Plain soils of the Mid-Atlantic region of the U.S.A., but fertility recommendations are dated and may need revising to match demand of current high-yielding soybean systems. Nineteen full-season soybean experiments were conducted during 2013 and 2014 in Virginia and northeastern North Carolina to correlate relative yield, V5-stage plant K concentration, and R2-stage trifoliate leaf K concentration with Mehlich-1 extractable soil K; establish critical tissue K concentrations for V5 and R2-stage soybean; and determine K fertilizer rate for maximum yield. Initial soil samples were taken prior to broadcasting across each replication. Potassium application rates were 0, 28, 56, 112, 168 and 224 kg K_2O ha^{-1} within two weeks of planting. Mehlich-1 extractable soil K ranged from 16 to 196 mg K kg^{-1}. Relative soybean yield of control plots ranged from 20 to 95%. Potassium application increased soybean yield at five sites with soil test K levels less than 40 mg K kg^{-1}. Yield declined with increasing K rate at one site. Critical soil test K was 38.8 mg K kg^{-1} with a relative yield of 88% at all sites. Critical V5 concentration was 18.2 g K kg^{-1} and critical R2 concentration was 24.6 g K kg^{-1}. These data indicated that current Virginia extension K fertilizer recommendations for soybean are sufficient under the environmental conditions experienced in this study.

Introduction

Potassium (K) is the one of the most important nutrients for high-yielding soybean [*Glycine max* (L.) Merr.]. Except for nitrogen, soybean requires more K than any other nutrient and affects plant water relations, enzyme activation, and photosynthetic processes (Fagaria, 2009, Havlin et al., 2004, Shingles and McCarty, 1994, Talbott et al., 1998, Tiwari, 2001). Soil K is not always in plant available form and regular fertilization is necessary to provide nutrients for crop uptake (Havlin et al., 2004). Current K fertilizer recommendations in the Mid-Atlantic U.S.A. are dated and may be inadequate to supply the fertilizer demand of higher yielding soybean. In 2013, farmers in the region harvested 1,314,419 hectares of soybean with a five-year average yield of 2,620 kg ha^{-1} (NASS, 2015). There has been little K research conducted with soybean in the Mid-Atlantic region, which is dominated by low cation exchange capacity (CEC) and low water-holding-capacity soils. The most recent research was conducted by Heckman and Kamprath (1995) on sandy loam and loamy sand soils in Clayton, NC, similar to soils found in the coastal plain of Virginia. In contrast, K research in soybean was recently performed by Slaton et al. (2010) in Arkansas and Clover and Mallarino (2012) in Iowa. In both studies, broadcast K fertilizer was necessary to increase plant K concentration as well as grain yield. Soil testing prior to fertilizer application and tissue testing at V5 and R2 was used to determine soil nutrient levels and plant K concentration at critical growth stages.

Potassium fertilizer application is necessary in nutrient limited soils to improve plant metabolic processes and increase soybean grain yield (Munson, 1985; Clover and Mallarino, 2012). In Arkansas, a study containing 34 site-years was conducted on silt loam soils containing 46 to 167 mg K kg^{-1} (Slaton et al., 2010). Soybean responded positively to K applications (applied at 0 to 148 kg K ha^{-1}) at all sites where Mehlich-3-extractable K was less than 91 mg K kg^{-1} and nine of 15 sites where extractable K ranged from 91 to 130 mg K kg^{-1}. In an Iowa study, K fertilization increased soybean yields when applied at rates of 71 to 117 kg K ha^{-1} at four of ten sites. On average, soybean yield responded linearly to K fertilizer application rates up to 103 kg K ha^{-1}. Soybean also responded to K applied to corn [*Zea mays* (L.) Merr.] in the previous growing season at three of 10 sites, where the linear yield response continued up to 168 kg K ha^{-1}, which was the maximum K fertilizer rate used (Clover and Mallarino, 2012). Although the Arkansas and Iowa research found relationships between soil test levels and response of soybean to K fertilization rate, soil types in those studies differ greatly than those found in the Mid-Atlantic region.

While soil testing is an important aspect of plant nutrient management and can help determine soil K levels, sampling only from the surface of a soil may result in erroneous K fertilizer recommendations. Yin and Vyn (2003) and Fernandez et al. (2008) sampled soil K at multiple horizon depths and found that soil in the surface 0 to 5 cm has significantly greater K concentration than that at 10 to 20 cm. In contrast, Evanylo (1991) suggested that leaching and accumulation of K at depths greater than 46 cm were responsible for the lack of response of no-till double-crop soybean to K fertilization. In that research, a Bojac loamy sand contained 96 (H-), 118 (H), or 106 (H) mg K ha^{-1} at 0 to 15, 15 to 30 and 30 to 46 cm depths, concentrations that should have occasionally resulted in a yield response. The author further suggested that the rate of K fertilizer should be adjusted with the amount of K found in the argillic horizon (subsurface horizon with significantly higher percentage of phyllosilicate clay than the overlaying soil material), the depth of which can vary greatly in coastal plain soils (Schaetzl and Anderson, 2005). Soybean roots can reach depths greater than the average sampling depth (0 to 15 cm for row crops) and it may be necessary to determine the concentration of K throughout the entire rooting zone in order to account for the total exchangeable K available for plant uptake. This is especially important in low CEC coastal plain and piedmont soils that are subject to leaching.

Tissue sampling can be a good indicator of nutrient status in plants. An Ontario study comparing three fertilizer placement methods, two conservation tillage systems, and two soybean row widths found that critical leaf K concentration at growth stage R1 (beginning bloom) (Fehr and Caviness, 1971) for maximum seed yield was approximately 24.3 g kg^{-1} (Yin and Vyn, 2004). In that study, K was applied at 100 kg K ha^{-1} as muriate of potash (KCl) and increased soybean leaf K concentrations by 5.1 to 8.0 g kg^{-1} (Yin and Vyn, 2003). In comparison, Clover and Mallarino (2012) determined that critical leaf K concentration for soybean at R1 was 17.6 to 20.0 g K kg^{-1} for maximum yield. Coale and Grove (1991) determined K content using atomic absorption spectrometry of whole soybean plants at R1. Total accumulation of K under high K fertility (88+ mg K kg^{-1} soil) was increased by 87 % at that soybean stage. Total dry matter was not affected by K fertility; therefore, total K accumulation was due to differences in K tissue concentration.

Seed composition may also be affected by fertilizer rates, which can affect germination and vigor. Yin and Vyn (2003) determined that seed K concentrations increased from 1.3 to 2.7 g kg^{-1} with K fertilizer applications. However, yield was not responsive in that study. Seed K concentrations might have significant influence on other seed attributes since K is widely involved in plant metabolic activities as an enzyme activator (Munson, 1985).

Results from previous research showed the importance of K in a soybean fertilization program. Potassium fertilization increased K content in the plant, improved metabolic processes, and in some cases increased yield (Clover and Mallarino, 2012, Coale and Grove, 1991, Yin and Vyn (2003). However, research is needed in coastal plain and piedmont soils to obtain data applicable to the Mid-Atlantic growing region. Results from this research can then be used to determine if K fertilizer recommendations in Virginia are adequate or are in need of revision. It is our hypothesis that following current Virginia K fertilizer recommendations will result in little to no deficiency or yield loss. We also hypothesize that yield will be maximized at soil K levels between 38 to 88 mg K kg^{-1} (medium soil test K category) and that plant tissue K sufficiency range will be between 17.5 and 25 g kg^{-1}, according to current Virginia recommendations (Donohue, 2001). The objective of this study was to determine full-season response to soil test K (STK) and K fertilization rates on Coastal Plain or Piedmont soils of Virginia and northeast North Carolina. Specifically, we will: 1) Correlate relative yield, V5-stage plant K concentration, and R2-stage trifoliate leaf K concentration with Mehlich-1 extractable soil K; 2) Establish critical tissue K concentrations for V5 and R2-stage soybean; and 3) calibrate K fertilization rate for maximum yield.

Materials and Methods

Nineteen field trials were conducted on soils representative of the Piedmont and Coastal Plain regions of Virginia and the northeastern Coastal Plain of North Carolina during 2013 and 2014 (Table 2.1). Maturity group IV or V soybeans were planted in conventional or no-till full-season systems (May-planted) with farmer owned or small plot equipment in 19- or 38-cm rows. Most test sites followed a two- or three-year crop rotation and previous crops included corn, soybean, or wheat [*Triticum aestivum* (L) Merr.]. Site seven in Campbell County was taken out of grape [*Vitis* vinifera. (L.) Merr.] production in 2013 and planted in soybean in 2014. There were also a few sites that were either previously fallowed or sown to grass sod or fescue [*Festuca arundinacea.* (L.) Merr.] hay crops (Table 2.1). In general, cultural practices and pest management followed North Carolina or Virginia Cooperative Extension recommendations. All sites were dry land and rainfall was near or above the 30-year average for most months in most locations in 2013 and near average in 2014 (Table 2.2).

Within two weeks of soybean planting and before fertilizer was applied, four composite soil samples per experiment (1 per replicate) consisting of 12 cores were collected at depths of 0 to 15, 15 to 30, or 30 to 60 cm within each replication. Soil samples were air-dried, ground, and sent to Virginia Tech soil testing laboratory for analysis using Mehlich I extraction procedures, which is the routine method used at that laboratory. Five grams of sieved, air-dried soil were placed into a 150 mL extraction flask, then 25 mL of Mehlich I extracting solution (0.05 *M* H_2SO_4 + 0.05 *M* HCl) was added and shook for 5 minutes on a reciprocating shaker set at 180 opm. The sample was filtered through a Whatman no. 2 filter paper and analyzed using inductively coupled plasma spectrometry (Helmke and Sparks, 1996). Table 2.3 lists average soil test K, estimated CEC and standard error for each site at the three sampling depths.

Each experiment was designed as a randomized complete block with four replications. Individual plot size was 3.8 m wide and 14.6 m long. After soil was sampled, K fertilizer was broadcast by hand on the surface of the soil (not incorporated) at 0, 28, 56, 112, 168, or 224 kg K ha^{-1} using granular muriate of potash (0-0-60). To ensure that other nutrients were non-limiting, fertilizer containing only those limiting nutrients was applied at the same time if needed and plants were monitored for deficiency symptoms other than K throughout the growing season.

To determine K concentration in the plant, tissue samples were taken at V5 (5th trifoliate) and R2 (full bloom), (Fehr and Caviness, 1977). At V5, samples consisted of 10 plants cut at ground level at random locations from each plot in 2013 and 1 m of row of whole plants cut at ground level from each plot in 2014. Twenty uppermost, fully developed soybean trifoliate leaves were randomly collected at the R2 stage from each plot in 2013 and 2014. Plant tissue for all V5 plants and R2 leaves were dried at 60° C and then ground using a Wiley Mill grinder with a 0.5 mm screen. Samples were then digested using nitric acid and hydrogen peroxide (EPA 3050 B) and then analyzed at Virginia Tech soil testing laboratory using inductively coupled atomic plasma mass spectrometry (ICAP).

Soybean was harvested at full maturity (R8) after seed moisture approached 130 g H_2O kg^{-1} seed using a small plot research combine equipped with scale and moisture tester. In 2013, plots were harvested with a 1.2 m-combine head, collecting seed from rows two through four in 30 cm-row tests and rows two through seven in 19 cm-row tests. In 2014, plots were harvested with a 1.5 m-combine head, collecting seed from rows two through five in 38-cm row experiments and rows two through nine in 19-cm experiments. Seed yield was adjusted to 130 g H_2O kg^{-1}.

Data were subjected to analysis of variance using the PROC GLM procedure of SAS. Fixed effects were K fertilizer rates and random effects were replications. A single degree of freedom contrast comparing the yield of soybean receiving no K against the average yield of soybean fertilized with K was performed to classify each site-year as responsive or unresponsive to K fertilization. Yield responses were interpreted as significant at $P < 0.10$.

Soil test K concentrations were highly variable between replications at some sites; therefore, STK and relative yields were not averaged over replications to perform regression analysis. To obtain relative yields, the yield of the unfertilized control (0 kg K_2O ha^{-1}) within each replication were divided by the highest yielding treatment receiving potassium fertilizer and multiplying by 100. Linear and quadratic relationships between relative seed yields and STK, V5 plant tissue, and R2-stage trifoliate-leaf tissue were defined using the PROC REG procedures of SAS. The Student's residual (<-2.5 and >2.5) and Cook's D statistics were used to identify outlying and influential observations, respectively. The outlying or influential observations were omitted from the dataset when appropriate and the model refit. Linear-plateau models were also fit to the same data using the PROC NLIN procedure of SAS. From these relationships, maximum relative yields were defined as 5% less than the predicted maximum for quadratic models or as the maximum value of each dependent variable defined by the predicted plateau of linear or quadratic-plateau models. When applicable, maximum yield definitions were used to identify the critical soil K availability index or tissue K concentration.

Calibration of K rates needed to maximize soybean yield were performed using linear and non-linear regression techniques. The minimum K fertilizer rate to maximize yield, determined by using Fisher's protected LSD at $P < 0.10$ for each site-year was regressed against the corresponding STK. Calibration was also performed with multiple regression techniques that included linear and quadratic terms for the STK and K fertilizer rate. For this calibration, relative yields were determined by dividing the treatment means by the highest yielding treatment mean in the test, then multiplying by 100. A significance level of $P = 0.10$ was used to include or exclude terms from the model.

Results and Discussion

Soil Testing

Soil test K at 0 to 15 cm depth ranged from 16 to 196 mg K kg^{-1} across the 19 sites (Tables 2.1 and 2.3). In general, STK decreased with depth (Table 2.3). However, STK increased with depth at sites 10 and 17. Higher STK concentrations at a deeper depth may indicate that the cation exchange capacity (CEC) of sandy textured soils was not adequate to hold the K nutrients and leaching occurred until a finer textured and higher CEC soil layer was reached (Evanylo, 1991). The CEC values at these sites were very low throughout the profile; therefore, leaching of K out of the topsoil would be likely.

Yield

Soybean yield increased over the unfertilized control at only five of the 19 sites (Table 2.4). In addition, yield decreased with K_2O fertilizer rate at site 5. There is no explanation as to why yield decreased at site 5, except that yield varied substantially within the site or this site may represent a false positive. Still, yield of control plots (0 kg K_2O ha^{-1} applied) was greater when compared to treated plots in three of four replications.

Soil test K at the 0 to 15 cm sampling depth from the sites that responded positively to K_20 fertilizer was 40, 17, 16, 22 and 28 mg K kg^{-1} soil at sites 8, 12, 13, 14 and 18 respectively (Table 2.1). A positive yield response was expected 40 to 85% of the time as the soils contained very little Mehlich-1 extractable K (Donahue, 2000). The remaining unresponsive sites had STK values ranging from 28 to 196 mg K kg^{-1}, two of which were classified as low, seven of which were classified as medium, and four classified as high. Yield response to K fertilizer is expected in low STK soils and sometimes in medium STK soils but almost never in high STK soils (Donahue, 2000). Therefore, many sites were not expected to differ from the control due to high STK levels, but a yield increase was expected on low and some of the medium testing sites. At sites 10 and 17, STK increased at the 30 to 60 cm depth which explains why those sites did not respond to K_2O fertilizer (Table 2.2). Regardless, these results do not appear to reflect the current guidelines. In our study, 26 % of sites were yield responsive to K_2O fertilizer compared to results from Iowa where four of 10 sites (40 %) responded positively to K_2O fertilizer (Clover and Mallarino, 2013) and from silt loam soils in Arkansas where 21 of 34 sites (62 %) responded positively to K_2O (Slaton et al., 2010). In Iowa, Bray extractable K of the responsive sites ranged from 130 to 154 mg K kg^{-1}. In Arkansas, Mehlich-3 extractable K of the responsive sites ranged from 41 to 131 kg K ha^{-1}. It is possible that lower CEC soils of the Coastal Plain and Piedmont regions of Virginia and northeastern North Carolina respond very differently from the Midwestern and silty loam soils of Arkansas. Regardless, maximum average yield occurred when 112 kg K_2O ha^{-1} was applied at sites 12 and 18, 168 kg K_2O ha^{-1} at site 14, and 224 kg K_2O ha^{-1}at sites 8 and 13 (Table 2.4).

Another explanation for the lack of response to K_2O fertilizer may be high STK variability between replicates within some experiments in this study, as shown by the standard errors in Table 2.3. For example, average 0 to 15 cm STK at site 7 was 37 mg K kg^{-1} with a standard error of 14.4, average 15 to 30 cm STK was 16 mg K kg^{-1} soil with a standard error of 5.42 and average 30 to 60 cm STK was 29 mg K kg^{-1} soil with a standard error of 14.26. Sites 6, 12, 17, 18, and 19 also had relatively high standard errors. Due to this variability within some experiments, four control (0 mg K ha^{-1}) relative yields, calculated by using the greatest yield within each replication, and the four corresponding STK values was used in the regression analysis instead of using relative yields and STK values that were averaged across replicates. The no-fertilizer control relative yields were regressed against STK values to investigate soil supply nutrient sufficiency (Fig. 2.1). Relative soybean yield increased at a diminishing rate to a maximum relative yield of 98% at 108 mg K kg^{-1} STK according to the quadratic model. Using the definition of maximum yield (maximum yield predicted minus 5%), the critical STK concentration to produce 93% relative yield was 88 mg K kg^{-1}. Nonlinear regression of these data indicated that relative yield reached a maximum of 88% at STK value of 38.8 mg K kg^{-1}, a value much lower than the quadratic model (Fig. 2.1). These critical points are much lower when compared to Slaton et al. (2010), where soybean yield was maximized at a relative yield of 95% when STK was 153 mg K kg^{-1} (Mehlich-3) when using a quadratic response and at 92% relative yield when STK was 108 mg K kg^{-1} (Mehlich-3) when using a linear plateau model. That research also showed that STK explained 76 to 79% of the yield variability among soils, but STK only explained 36 to 52% of the STK variability in these experiments.

V5 Tissue Analysis

Total K uptake in the soybean plant at the V5 growth stage was positively correlated with K fertilizer additions in eleven of nineteen sites, even though there was no consistent yield response at seven of those sites (Tables 2.4 and 2.5). Although a yield response was not always realized, the soybean plants were taking up and utilizing soil applied K fertilizer for growth and development. The linear plateau model relating relative yield to V5 K uptake indicated a critical V5 plant K concentration to be 18.2 g K kg^{-1} (Fig. 2.2). After that plant concentration, relative yield plateaued around 80%. Using the quadratic model, the maximum relative yield was 80% when V5 plant K concentration was near 25 mg K kg^{-1}. Although the R^2 value of the linear plateau and quadratic model (both 0.25) was low, critical V5 plant K concentration falls within or above the sufficiency range (15 to 22.5 g K kg^{-1}) for young soybean, as determined by Sabbe et al. 2011 and Bryson et. al, 2014.

R2 Tissue Analysis

Plant K concentrations at R2 increased in response to K fertilizer application at all but four sites, two of which (8, 10) were non-significant with P-values of 0.1027 and 0.1328, respectively, (Table 2.6). The linear plateau model (Fig. 2.3) estimated critical R2 trifoliate K concentration for maximum relative yield of 82% to be 24.6 g K kg^{-1}, which is comparable to Yin and Vyn (2002) and greater than Clover and Mallarino (2012). In contrast to Farmaha et al. (2012), R2 soybean in this study has a greater critical concentration than V5 soybean. The quadratic response (Fig. 2.3) of relative yield to R2 K concentration was similar to the linear plateau model of relative yield to R2 K concentration.

Fertilizer Calibration

Regression analysis for calibration of the minimum fertilizer rate necessary to maximize yield at various STK levels was not significant with the quadratic model (P = 0.3412) but only slightly non-significant in the linear model (P= 0.1146) (Fig. 2.4). The second fertilizer calibration curve was developed to determine how much K fertilizer is necessary based on STK levels in order to achieve optimum yield (Fig. 2.5). In general, more fertilizer is needed to increase yield at low STK levels. For example, at STK levels of 50 mg K kg^{-1}, 25 kg ha^{-1} K_2O fertilizer would produce 90% relative yield but if 100 kg ha^{-1} K_2O fertilizer were applied, relative yield would be near 100%. At a soil test level of 20 mg K kg^{-1}, an application of 25 kg K_2O ha^{-1} would produce 50% relative yield where 200 kg K_2O ha^{-1} would be necessary to produce near 100% relative yield.

Conclusions

Potassium fertilization increased soybean yield at only five of 19 sites in this study. Yield response was expected at all of those sites when 0 to 15 cm STK was ≤40 mg K kg^{-1}. Yield was expected to increase with K fertilizer at four other sites where STK ranged from 28 to 43 mg K kg^{-1}, but no yield increase was observed. Variability in measured soil test K levels between replications at some locations may have distorted these results, but non-linear regression of STK and 0 K rate controls using all data (not just average values over replicates) also indicated no yield increase with K fertilizer if STK was greater than 38.8 mg K kg^{-1}. These data did support our hypotheses that current Virginia K fertilizer recommendations will result in little to no yield loss and that yield will be maximized at STK levels between 38 to 88 mg K kg^{-1}. Plant tissue analysis also supported our hypothesis that plant tissue K sufficiency at R2 will range between 17.5 and 25 g kg^{-1}. Four of five yield-responsive sites were responsive to K fertilizer at R2 as well. The multiple regression calibration follows current Virginia Cooperative Extension recommendation guidelines and is similar to the linear plateau model shown in Fig. 2.1. At low STK levels, greater amounts of fertilizer are necessary to maximize yield and prevent deficiency. Critical STK for yield response to K was 38.8 mg K kg^{-1} and 88% relative yield.

Overall, our results indicated that K is an important soybean nutrient and regular K fertilization is necessary to prevent yield loss and in some soil types with low to medium STK levels. Most sites had sufficient rainfall in 2013 and 2014 which could have alleviated plant stress that is typical in hot, dry summers. In drier years, plants have less access to soil K and therefore could benefit from extra K fertilizer being applied. Therefore, more data is needed in future years, with different weather patterns, to determine if current extension recommendations are indeed sufficient.

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Table 2.1. Location, previous crop, soil texture, soil characterization and Mehlich-1 extractable nutrient concentration information from 0 to 15 cm depth for 19 field trials on Piedmont and Coastal Plain soils of North Carolina and Virginia.

Site	**Year**	**County/City**	**Previous Crop**	**Soil Series and Texture**	**Classification**	**OM†**	**CEC†**	**pH**	**K**	**P**	**Ca**	**Mg**
						----g kg^{-1}----			-----------mg kg^{-1}----------			
1	2013	Accomack, VA	Wheat Cover Crop	Sandy loam	Typic Hapludults	2.1	7.8	6.4	179	67	1286	146
2	2013	Culpeper, VA	Wheat	Silty clay loam	Ultic Hapludalfs	0.8	3.4	6.5	94	100	511	61
3	2013	Culpeper, VA	Wheat	Silty clay loam	Ultic Hapludalfs	2.4	8.1	6.6	54	15	1376	122
4	2013	Culpeper, VA	Wheat	Silty clay loam	Ultic Hapludalfs	2.7	8.6	5.5	196	72	911	131
5	2013	Suffolk, VA	Fallow	Loamy fine sand	Aquic Hapludults	0.9	2.4	6.0	74	52	332	35
6	2013	Virginia Beach, VA	Corn	Loam	Typic Hapludults	3.1	7.1	5.7	82	48	815	119
7	2014	Campbell, VA	Soybean and Grapes	Fine sandy loam	Typic Kanhapludults	2.6	6.4	6.5	43	38	916	83
8	2014	Chesapeake, VA	Sod	Sandy loam	Typic Hapludults	1.8	5.3	5.4	40	142	521	61
9	2014	Currituck, NC	Soybean	Loamy sand	Typic Hapludults	1.7	4.8	5.2	90	149	447	49
10	2014	Gates, NC	Soybean	Fine sandy loam	Aquic Paleudults	1.0	3.4	6.4	52	47	514	82
11	2014	Gates, NC	Soybean	Loam	Typic Albaquults	0.9	2.4	5.6	43	53	201	46
12	2014	Lunenburg, VA	Soybean	Sandy loam	Typic Kanhapludults	3.3	5.2	6.3	17	19	671	142
13	2014	Mecklenburg, VA	Fescue Hay	Fine sandy loam	Typic Kanhapludults	2.0	4.6	6.7	16	9	650	152
14	2014	Mecklenburg, VA	Soybean	Fine sandy loam	Aquic Hapludults	1.3	2.8	5.4	22	25	326	49
15	2014	Northumberland, VA	Corn	Fine sandy loam	Aquic Hapludults	1.7	4.6	6.8	83	29	605	164
16	2014	Richmond, VA	Fescue Hay	Fine sandy loam	Typic Endoquults	1.4	2.2	5.3	38	3	108	21
17	2014	Suffolk, VA	Corn	Fine sandy loam	Typic Hapludults	0.8	2.2	5.6	28	56	248	45
18	2014	Virginia Beach, VA	Corn	Fine sandy loam	Aeric Endaquults	3.3	5.5	5.7	28	37	545	91
19	2014	Westmoreland, VA	Corn	Sandy loam	Typic Hapludults	1.9	4.3	6.4	50	5	515	148

†OM, organic matter; CEC, estimated cation exchange capacity

Table 2.2. Average monthly temperature (°C) and rainfall (cm) obtained from closest weather station to each full-season site. Surplus or deficit of rainfall, compared to 30-year average, is listed in parentheses.

Site(s)	Location	May	June	July	August	September	October
1	**Accomack, VA**						
	Rain	2.3 (-6.1)	9.5 (-0.5)	6.2 (-6.6)	7.1 (-3.8)	2.7 (-7.3)	10.2 (1.1)
	Temp	19.4 (0.8)	24.3 (0.8)	27.4 (1.5)	24.3 (-0.6)	20.7 (-0.9)	18.9 (2.9)
2,3,4	**Culpeper, VA**						
	Rain	8.0 (-2.6)	24.7 (14.4)	20.0 (11.6)	9.7 (1.9)	12.8 (1.4)	8.8 (0.8)
	Temp	17.7 (0.8)	23.2 (1.4)	25.6 (1.6)	23.7 (0.4)	20.7 (1.5)	16.2 (2.8)
5	**Suffolk, VA**						
	Rain	7.1 (-2.6)	21.2 (10.1)	17.4 (4.3)	12.9 (-1.6)	4.6 (-8.9)	16.8 (7.6)
	Temp	19.3 (0.0)	24.2 (0.4)	26.3 (0.3)	24.1 (-1.0)	20.6 (-1.3)	17.0 (0.7)
6	**Virginia Beach**						
	Rain	4.5 (-4.0)	4.5 (-6.0)	24.9 (12.3)	5.9 (-7.2)	16.8 (6.4)	3.0 (-5.7)
	Temp	23.0 (4.2)	25.6 (2.0)	26.9 (0.8)	26.1 (0.9)	24.5 (2.4)	19.0 (2.5)
7	**Campbell, VA**						
	Rain	13.7 (3.8)	6.1 (1.7)	14.7 (4.2)	12.1 (3.6)	4.1 (-5.3)	9.1 (0.5)
	Temp	18.9 (2.2)	23.0 (1.6)	23.5 (0.2)	22.0 (-0.7)	20.0 (0.7)	13.9 (1.0)
8,18	**Chesapeake, Virginia Beach, VA**						
	Rain	6.0 (-2.6)	7.9 (-2.6)	14.5 (1.8)	13.7 (0.6)	28.9 (18,5)	3.7 (-5.0)
	Temp	20.8 (1.9)	23.9 (0.2)	25.2 (-0.9)	24.4 (-0.9)	23 (0.9)	18.4 (1.9)
9	**Currituck, NC**						
	Rain	9.7 (1.2)	11.1 (0.6)	21.2 (8.6)	9.4 (-3.7)	13.5 (3.1)	2.3 (-6.5)
	Temp	21.5 (2.7)	24.5 (0.9)	25.7 (-0.4)	25.1 (-0.1)	23.1 (0.9)	17.7 (1.2)
10,11	**Gates, NC**						
	Rain	7.9 (-1.8)	22.3 (11.2)	15.7 (2.7)	6.6 (-7.9)	18.4 (4.9)	3.8 (-5.4)
	Temp	21.3 (2.0)	24.0 (0.1)	24.4 (-1.6)	23.2 (-1.9)	22.2 (0.3)	16.3 (0.0)
12,13,14	**Lunenburg, Mecklenburg, VA**						
	Rain	13.1 (3.0)	2.8 (-6.4)	8.5 (-2.8)	5.8 (-5.5)	12.7 (2.3)	7.7 (-1.3)
	Temp	20.6 (1.9)	24.5 (0.9)	25.1 (-0.7)	23.8 (-1.1)	21.8 (0.8)	16.6 (1.9)
15	**Northumberland, VA**						
	Rain	9.7 (-0.8)	6.5 (-2.5)	9.0 (-2.6)	11.1 (-0.7)	7.6 (-3.2)	8.7 (-0.1)
	Temp	19.1 (-0.2)	23.6 (-0.3)	24.7 (-1.3)	23.0 (-2.0)	21.1 (-0.3)	16.4 (0.8)
16,19	**Richmond, Westmoreland, VA**						
	Rain	11.3 (0.7)	7.7 (-1.3)	7.7 (-3.9)	9.1 (-2.6)	6.9 (3.9)	5.1 (-3.7)
	Temp	19.8 (0.6)	23.3 (-0.6)	24.4 (-1.6)	22.8 (-2.3)	21.0 (-0.4)	15.8 (0.3)
17	**Suffolk, VA**						
	Rain	6.6 (-3.2)	8.8 (-2.3)	16.1 (3.0)	5.6 (-8.9)	15.3 (1.8)	3.1 (-6.1)
	Temp	20 (0.7)	23.1 (-0.8)	24.1 (-1.9)	23.2 (-1.8)	21.65 (-0.2)	16.1 (-0.2)

Table 2.3. Average Mehlich-I extractable K, standard error and estimated CEC at three sampling depths for 19 sites of full season soybean studies in Piedmont and Coastal Plain soils of North Carolina and Virginia

Site	**Year**	**County/City**	**0-15 cm**		**15-30 cm**		**30-60 cm**	
			CEC†	**Soil K ‡**	**CEC†**	**Soil K ‡**	**CEC†**	**Soil K ‡**
			g kg^{-1}	mg K kg^{-}	g kg^{-1}	mg K kg^{-1}	g kg^{-1}	mg K kg^{-1}
1	2013	Accomack, VA	8.8	179 ± 13.5	7.7	85 ± 8.9	6.2	46 ± 5.8
2	2013	Culpeper, VA	3.4	94 ± 6.0	2.8	66 ± 6.8	3.1	69 ± 6.8
3	2013	Culpeper, VA	8.1	54 ± 3.0	6.3	24 ± 1.7	7.6	19 ± 1.7
4	2013	Culpeper, VA	8.6	196 ± 11.3	7.7	134 ± 7.3	6.6	105 ± 14.6
5	2013	Suffolk, VA	2.4	74 ± 2.0	2.1	52 ± 3.1	2.1	60 ± 4.8
6	2013	Virginia Beach, VA	7.1	82 ± 8.9	4.0	38 ± 2.9	3.6	36 ± 9.8
7	2014	Campbell, VA	6.4	37 ± 14.4	4.7	16 ± 5.4	4.2	29 ± 14.3
8	2014	Chesapeake, VA	5.3	40 ± 2.7	4.2	31 ± 1.9	3.4	28 ± 2.5
9	2014	Currituck, NC	4.8	90 ± 3.1	4.1	69 ± 2.1	3.7	60 ± 2.4
10	2014	Gates, NC	3.4	52 ± 4.1	2.8	50 ± 0.9	3.6	72 ± 5.0
11	2014	Gates, NC	2.4	43 ± 2.1	1.9	32 ± 1.5	1.4	27 ± 2.4
12	2014	Lunenburg, VA	5.2	17 ± 1.3	4.1	13 ± 1.4	4.4	9 ± 0.5
13	2014	Mecklenburg, VA	4.6	16 ± 2.0	3.3	11 ± 1.1	3.8	11 ± 1.0
14	2014	Mecklenburg, VA	2.8	22 ± 0.5	1.8	13 ± 1.0	2.9	14 ± 1.7
15	2014	Northumberland, VA	4.6	83 ± 5.5	3.2	76 ± 7.4	3.5	74 ± 7.8
16	2014	Richmond, VA	2.3	38 ± 1.9	1.4	25 ± 2.2	1.8	27 ± 1.9
17	2014	Suffolk, VA	2.2	28 ± 4.4	1.6	29 ± 1.9	1.4	43 ± 0.8
18	2014	Virginia Beach, VA	5.5	28 ± 4.4	3.3	17 ± 1.0	1.7	16 ± 1.4
19	2014	Westmoreland, VA	4.3	50 ± 9.0	4.1	33 ± 6.1	4.3	27 ± 3.9

† CEC – Cation Exchange Capacity

‡ Soil K concentration, mg K kg^{-1} ± Standard Error

Table 2.4. Full-season soybean actual and relative yields as affected by K fertilizer rate at 19 site years on Coastal Plain and Piedmont soils in North Carolina and Virginia

		K_2O Fertilizer Rate, kg ha^{-1}							
Site	**RY†**	**0**	**28**	**56**	**112**	**168**	**224**	**Sdf ‡**	**LSD**
	-%-	**--------------------------------kg ha^{-1}--------------------------------**							
1	92	3496	3629	3785	3597	3238	3506	0.686	NS §
2	72	3366	4093	3823	3224	3921	3616	0.3744	NS
3	93	3737	3800	3433	3495	3815	3401	0.4413	NS
4	93	4334	4085	3888	4436	3920	3683	0.2706	NS
5	95	3486	2956	2939	2872	2989	2509	0.0061	450
6	86	3915	4076	4014	3991	3851	4097	0.7363	NS
7	77	2735	2996	3078	2605	2917	3492	0.4525	NS
8	78	3194	3463	3614	3697	3914	3996	<.0001	185
9	79	2450	2990	2196	2765	2289	2507	0.7986	NS
10	94	4839	4782	4134	4245	4971	4839	0.3875	NS
11	86	3221	3023	2955	3259	2841	3079	0.5929	NS
12	20	581	1327	2031	2591	2578	2559	<.0001	252
13	32	1227	1465	2155	3034	3238	3871	0.0006	750
14	36	1056	1414	1624	1933	2492	2480	0.0014	541
15	93	4869	5025	4947	4806	4778	4813	0.9789	NS
16	75	1754	1889	1907	1898	1838	1881	0.5615	NS
17	66	1457	1534	1785	2012	2216	1762	0.4625	NS
18	71	2703	2504	3134	3579	3159	3374	0.0876	553
19	92	3329	3299	3352	3242	3337	3434	0.9713	NS

† RY, relative yield of soybean receiving no K fertilizer compared to maximum numerical yield of soybean receiving K fertilizer

‡ sdf, single-degree-of-freedom contrast P value comparing the yield of soybean receiving no K to the yield of soybean receiving K

§ NS, not significant (*P*>0.10)

Table 2.5. Mean actual whole plant K concentration at V5 growth stage of soybean as affected by K fertilizer rates at 19 sites on Coastal Plain and Piedmont soils in North Carolina and Virginia.

	K$_2$O Fertilizer Rate, kg ha^{-1}							
Site	**0**	**28**	**56**	**112**	**168**	**224**	**Sdf†**	**LSD**
	----------------g K kg^{-1}----------------							
1	26.3	26.4	27.0	27.4	27.7	26.1	0.2944	NS‡
2	14.0	9.9	10.0	16.3	16.3	13.5	0.7618	NS
3	28.0	25.5	26.6	26.1	22.8	24.9	0.2187	NS
4	21.9	24.0	24.4	25.9	26.5	25.9	0.0204	3.0
5	23.1	22.7	22.9	24.3	25.0	24.5	0.6003	NS
6	19.2	18.8	23.8	22.0	22.1	23.0	0.0605	3.0
7	18.4	18.1	19.7	17.8	24.3	22.1	0.3251	NS
8	12.2	15.4	17.9	16.9	17.7	19.1	0.0012	3.0
9	33.0	33.2	34.1	32.5	35.1	35.1	0.3576	NS
10	19.1	23.2	20.4	25.1	27.8	28.0	0.001	3.2
11	18.7	17.7	21.5	21.3	22.5	24.8	0.1096	NS
12	5.0	11.0	13.9	13.0	17.0	20.0	<.0001	3.0
13	10.1	16.1	20.2	21.8	27.8	27.7	0.0008	6.8
14	12.2	16.8	22.7	25.7	26.0	29.6	<.0001	3.7
15	26.9	28.0	28.7	27.1	28.1	26.5	0.4835	NS
16	22.6	23.0	24.5	28.0	26.8	24.5	0.0195	2.4
17	14.9	20.7	21.6	21.1	26.5	27.5	<.0001	3.5
18	13.1	17.1	18.0	18.8	19.0	21.0	0.0242	5.1
19	22.2	26.9	27.8	28.9	30.8	28.1	0.0026	3.9

†sdf, single-degree-of-freedom contrast P value comparing the concentration of soybean receiving no K to the concentration of soybean receiving K

‡NS, not significant (*P*>0.10)

Table 2.6. Mean actual trifoliate K concentration at R2 growth stage of soybean as affected by K fertilizer rates at 19 sites on Coastal Plain and Piedmont soils in North Carolina and Virginia.

	K_2O Fertilizer Rate, kg ha^{-1}							
Site	**0**	**28**	**56**	**112**	**168**	**224**	**Sdf†**	**LSD**
	----------------g K kg^{-1}----------------							
1	24.7	25.2	24.6	25.8	25.4	25.7	0.3510	NS
2	14.9	15.7	16.3	17.1	17.5	20.0	0.0721	2.9
3	28.9	30.1	28.7	27.9	28.2	28.6	0.8976	NS
4	26.6	27.7	28.3	30.6	29.6	30.4	0.029	2.6
5	17.8	19.2	19.3	20.0	20.0	20.1	0.0071	1.4
6	18.7	19.6	22.8	24.0	22.1	24.0	0.0342	3.7
7	13.5	17.7	18.3	19.5	19.2	19.5	0.0042	3.4
8	19.4	21.0	21.3	21.6	25.1	22.1	0.1027	NS
9	23.1	24.6	24.0	23.7	24.5	23.5	0.0911	1.2
10	21.2	23.2	22.0	22.2	25.2	25.1	0.1328	NS
11	16.4	18.7	19.4	20.1	20.9	24.1	0.0002	2.0
12	7.8	14.6	19.6	18.3	17.6	22.0	<.0001	4.5
13	8.7	16.3	18.3	19.3	21.2	23.4	<.0001	2.0
14	18.1	19.2	21.7	23.1	24.0	26.0	0.0058	3.3
15	26.8	28.0	28.0	27.4	30.1	28.8	0.0054	1.2
16	25.3	25.6	26.8	26.9	28.6	28.0	0.0334	1.8
17	16.3	20.1	18.3	20.1	23.1	23.0	0.0021	2.8
18	20.7	22.5	22.6	24.0	25.0	24.8	0.0731	3.9
19	18.1	20.0	20.6	22.1	23.4	24.1	<.0001	1.7

† sdf, single-degree-of-freedom contrast P value comparing the concentration of soybean receiving no K to the concentration of soybean receiving K

Table 2.7. Coefficient values for calibration of K fertilizer rate using a multiple regression model where relative yield is predicted from extractable soil K and K fertilizer rate at 6 responsive sites

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr>F**
Soil K 0-15 cm	1	4805.74	7805.74	68.97	<.0001
Fertilizer Rate	1	4028.72	4028.72	57.82	<.0001
Soil K*Soil K	1	2132.04	2132.04	30.60	<.0001
Fertilizer*Fertilizer	1	371.15	371.15	5.53	0.0281
Soil K *Fertilizer	1	5042.84	5042.84	72.38	<.0001

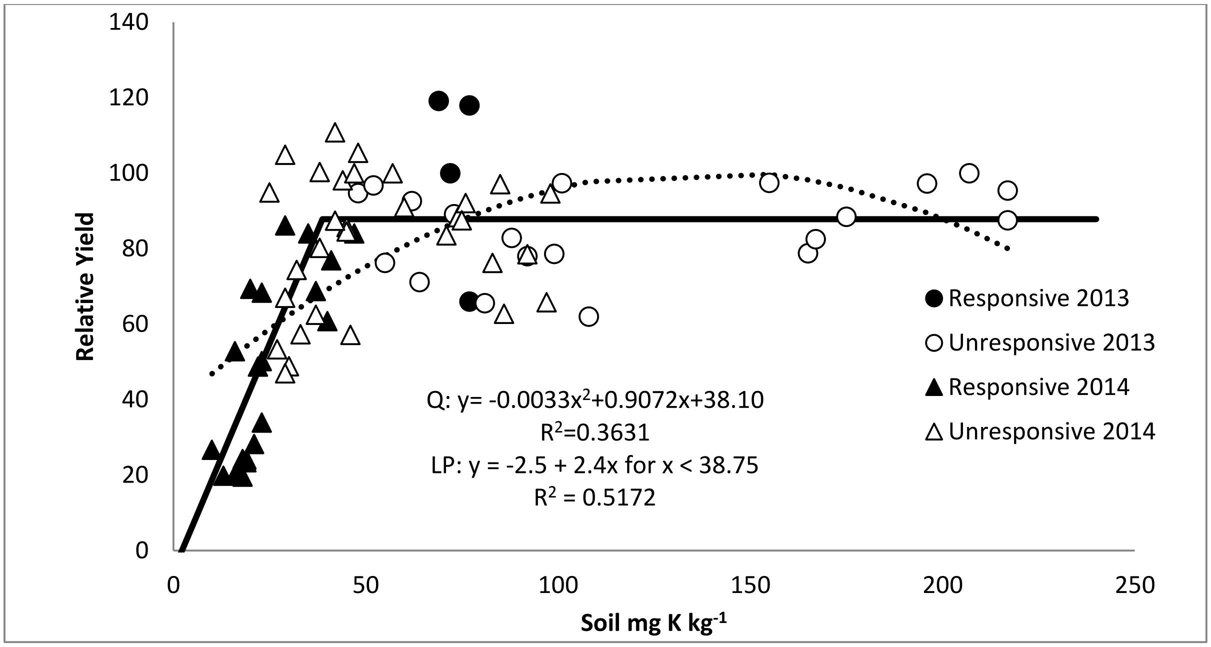

Figure 2.1. Relative soybean yield for each replication regressed against Mehlich-1 extractable soil K as predicted with a quadratic or linear plateau model. The classification of a site as responsive ($P < 0.10$) or non-responsive ($P > 0.10$) was based on single degree of freedom contrasts that indicate whether the yield of fertilized plots was different from the non-fertilized control.

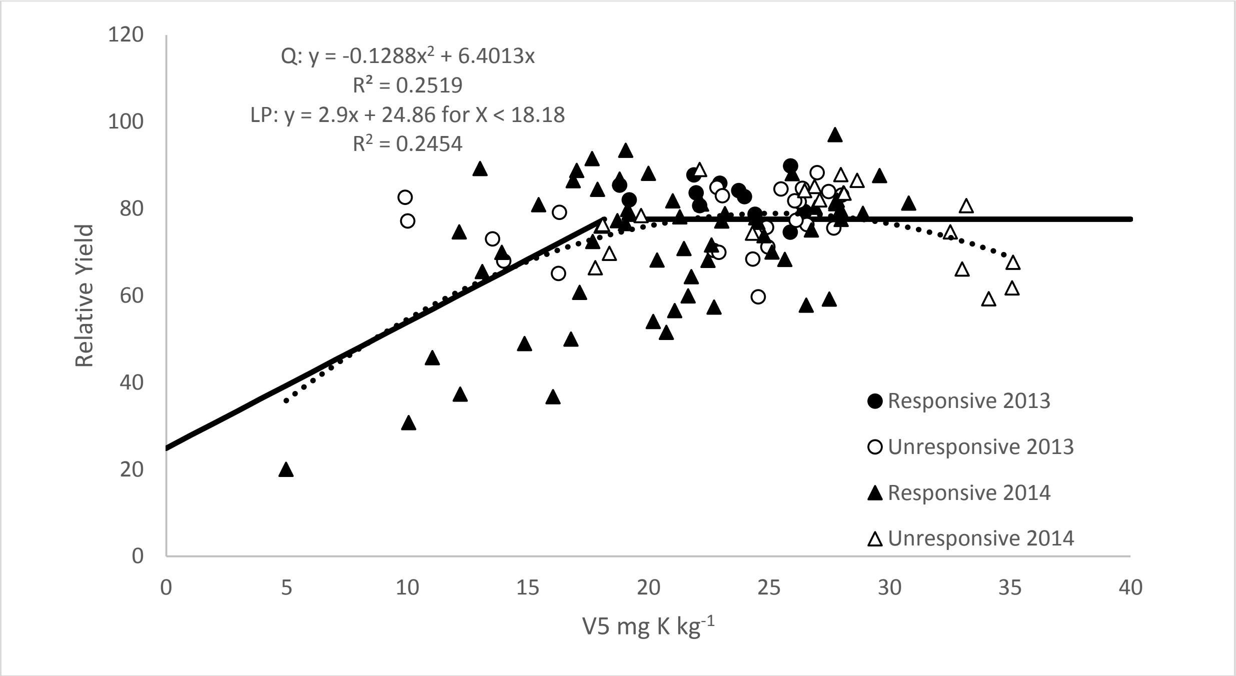

Figure. 2.2. Relative soybean yield averaged across treatments regressed against V5 K concentration as predicted with a quadratic or linear plateau model. The classification of a site as responsive ($P < 0.10$) or non-responsive ($P > 0.10$) was based on single degree of freedom contrasts that indicate whether the yield of fertilized plots was different from the non-fertilized control.

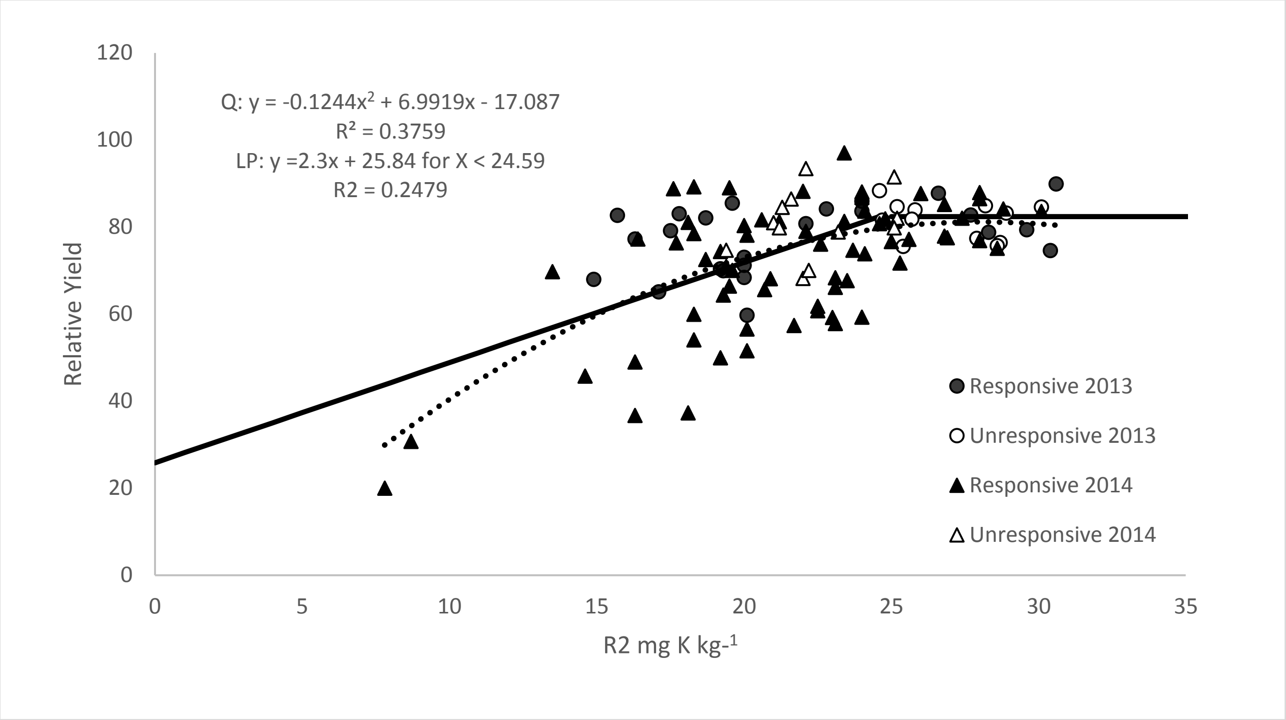

Figure 2.3. Relative soybean yield regressed against R2 K concentration as predicted with a quadratic or linear plateau model. The classification of a site as responsive ($P < 0.10$) or non-responsive ($P > 0.10$) was based on single degree of freedom contrasts that indicate whether the yield of fertilized plots was different from the non-fertilized control.

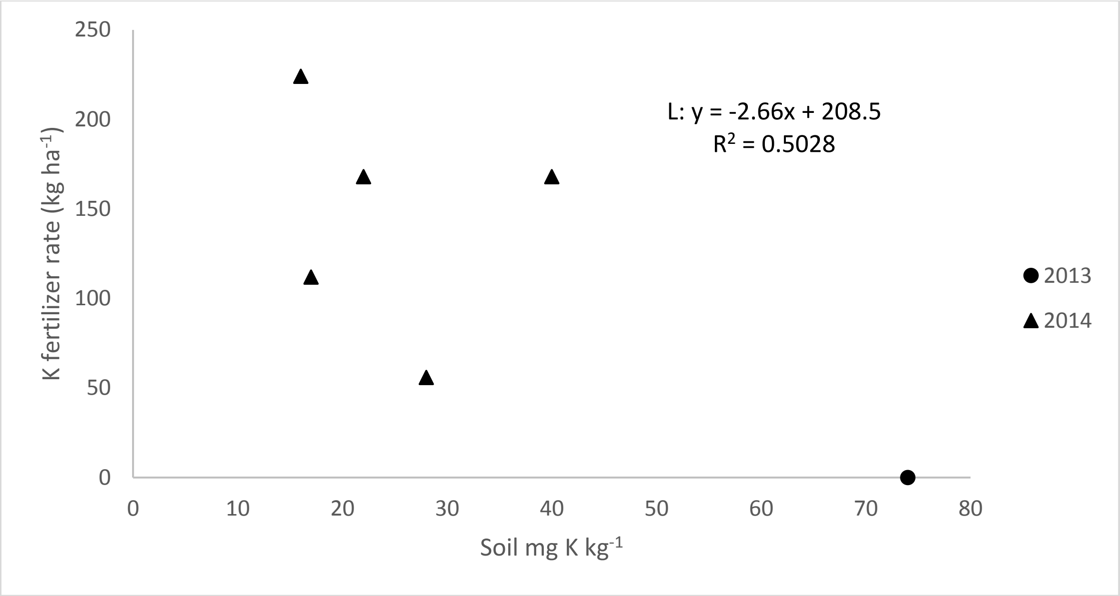

Figure 2.4. Calibration of K fertilizer rate (kg ha-1) where minimum K fertilizer rate needed to maximize yield is compared to the corresponding STK (mg K kg-1) for responsive sites only. Neither linear nor quadratic responses were significant.

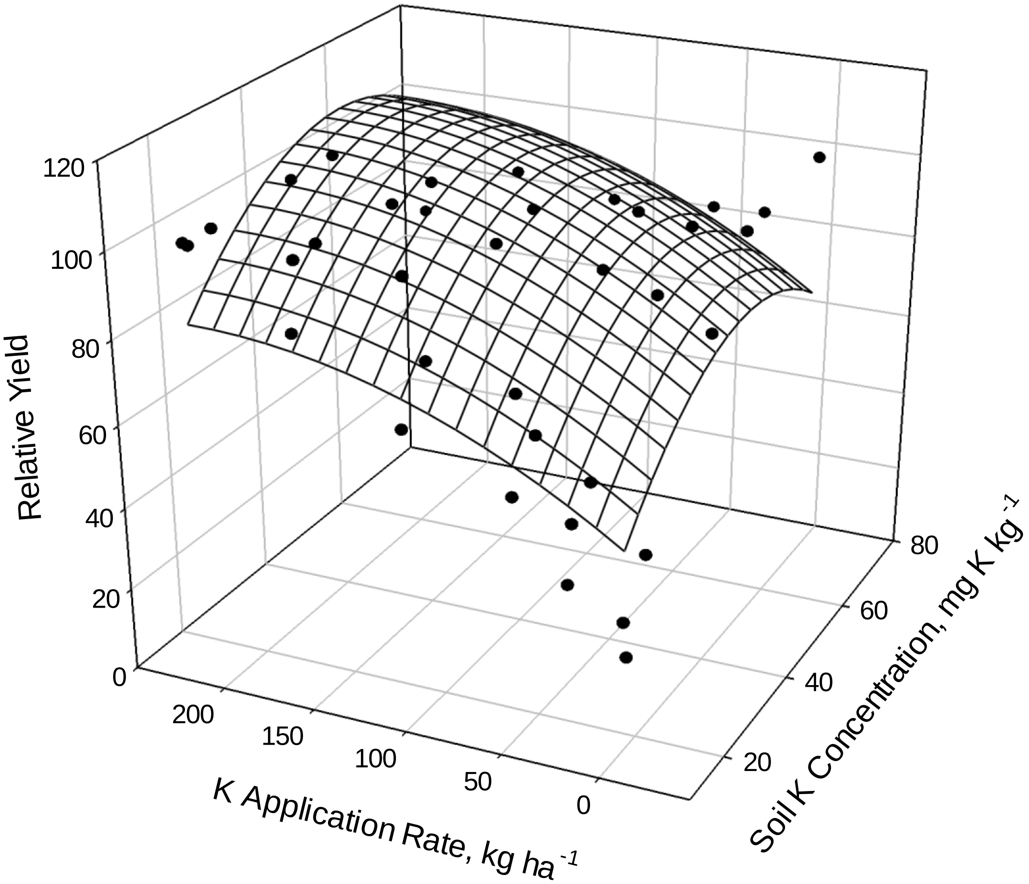

Figure 2.5. Calibration of K fertilizer rate using a multiple regression model where relative yield is predicted from extractable soil K and K fertilizer rate. Coefficient values for the regression model are listed in Table 2.7.

Chapter 3 – Double-Crop Soybean Response to Potassium on Coastal Plain and Piedmont Soils of Virginia

ABSTRACT

Potassium nutrition is important to double-crop soybean [*Glycine max* (L.) Merr.] systems in order to achieve high yields on Piedmont and Coastal Plain soils of the Mid-Atlantic U.S.A region, but current fertilizer recommendations are dated and possibly need revisions. Fourteen double-crop soybean experiments were conducted during 2013 and 2014 in Virginia to correlate relative yield, V5 plant K concentration and R2 trifoliate leaf K concentration with Mehlich-1 extractable soil K; establish critical K concentrations for V5 and R2 stage in soybean; determine average wheat [*Triticum aestivum* (L.) Merr.] K removal by straw and chaff; and calibrate K fertilizer rate for maximum yield. Experiments were designated as wheat straw remaining or straw removed, dependent on location. Initial soil samples at 0 to 15, 15 to 30 and 30 to 60 cm were taken prior to broadcasting 0, 28, 56, 112, 168 and 224 kg K_2O ha^{-1} within two weeks of planting. Mehlich-1 extractable soil K ranged from 30 to 177 mg K kg^{-1} and resulted in relative yields of 80 to 99% when no K fertilizer was applied. Potassium fertilizer increased soybean yield at only one site, but yield declined with increasing K rate at another site. Critical concentrations could not be determined for V5 and R2 soybean. These data indicated that at higher soil test K levels and with ample summer rainfall, current extension recommendations are sufficient but more experiments are needed at lower soil test K levels to determine if current recommendations are sufficient for our region.

Introduction

Potassium (K) is an essential plant nutrient that affects photosynthesis; helps regulate turgor pressure, which in turn reduces water loss and plant wilting; aids the translocation of sugars and starches; and builds cellulose to reduce lodging (Fagaria, 2009, Havlin et al., 2004, Shingles and McCarty, 1994, Talbott et al., 1998, Tiwari, 2001). With the exception of nitrogen, K is needed in greater amounts than other nutrients, but is not always available in exchangeable form in the soil. Therefore, it becomes necessary to apply K fertilizer to prevent or reduce the likelihood of K deficiency in soybean [*Glycine max* (L.) Merr.] (Havlin et al., 2004).

Double-crop soybean systems are widely used in the Mid-Atlantic U.S.A. region and can be more profitable than monoculture soybean systems since two crops can be grown and harvested within a single year (Farno et al., 2002). There were 1.3 million hectares of soybean harvested in the Mid-Atlantic in 2013, of which 42% were double-cropped (NASS, 2015).

Soils with low cation exchange capacity (CEC) and low water holding capacity are prevalent in the Mid-Atlantic and there has been little research conducted on these types of soils, especially in double-crop systems. The most recent double-crop research was conducted by Evanylo (1991) on loamy sand coastal plain soils in Painter VA. He concluded that leaching and accumulation of K at depths greater than 46 cm were responsible for lack of response to K fertilization. Typically, soil K levels decrease after the first 0 to 5 cm and have been found to have significantly greater K concentration than those at 10 to 20 cm (Fernandez et al., 2008; Yin and Vyn, 2003). But in Evanylo's research, the Bojac loamy sand contained 96, 118, or 106 mg K ha^{-1} at 0 to 15, 15 to 30, or 30 to 46 cm, respectively. Furthermore, although the average sampling depth for row crops is 0 to 15 cm, soybean roots can reach much greater depths than that and soil sampling at depth is necessary to determine K levels throughout the whole soil profile. As stated by Heckman and Kamprath (1995), the taproot of a soybean can utilize soil reserves differently than the fibrous root system of corn. Evanylo further suggested that K fertilizer application rate should be adjusted based on the amount of K present in the argillic horizon, which can vary in coastal plain soils. Woodruf and Parks (1980) also suggested that soybean could obtain more K from the B horizon on South Carolina coastal plain soils than corn. Therefore, sampling depth may be especially important throughout the coastal plain and piedmont region due to low CEC soils that are susceptible to leaching.

Although not in a double-crop system, Heckman and Kamprath (1995) conducted K research in Clayton, NC on loamy sand and sandy loam soils, similar to those found in the Coastal Plain of Virginia. The researchers saw linear increases in tissue concentration at 11, 35, 49 and 77 days after planting with broadcast K fertilizer application. Also, high yields were associated with high plant K concentrations with average concentrations at 77 days of 29.6, 30.7 or 25.6 g K kg^{-1} in 1985, 1986 or 1987, respectively. Heckman and Kamprath also found a positive correlation with grain yield and leaf and petiole K concentration, even though K concentrations in that study were above a critical value of 22.0 g K kg^{-1}, as reported by Melsted et al. (1969). Although neither in the Mid-Atlantic region nor on double-crop soybean, K research in soybean was recently performed by Clover and Mallarino (2012) in Iowa and Slaton et al. (2010) in Arkansas. Broadcast K fertilization increased plant K concentration and grain yield in each study. However, in the Iowa study, K fertilization at rates of 71 to 177 kg K ha^{-1} increased soybean yields at four of ten sites and soybean yield responded linearly at various K application rates up to 103 kg K ha^{-1} (Clover and Mallarino, 2012). In the Arkansas study, conducted on 34 silt loam soils ranging from 46 to 167 mg K kg^{-1}, soybean yield responded positively at all sites where Mehlich-3 extractable K was less than 91 mg K kg^{-1} and K fertilizer applications ranged from of 0 to 148 kg K ha^{-1}. In addition, nine of 15 sites where extractable K ranged from 91 to 130 mg K kg^{-1}, had positive yield response. While these studies related soybean response to K fertilizer rate and to soil test levels, those soil types vary greatly from

Mid-Atlantic soils and research is needed within the region to reassess current fertilizer recommendations.

Potassium uptake in wheat may have an influence on nutrient availability for the following soybean crop. Nutrients remaining in the stem and chaff can be utilized by double-crop soybean and reduce fertilizer input. A United Kingdom study on removal of P and K from the soil in wheat [*Triticum aevestum* (L.) Merr.] and barley [*Hordeum vulgare* (L.) Merr.] straw resulted in median straw removal of 0.07% total P and 100% total K in the soil (Withers, 1991). Potassium concentrations in 1986 through 1988 were significantly different with 1988 being greatest and 1986 being least. The literature states that it was a very wet at harvest in southeast England, but very dry at harvest in southwest England in 1987. Wheat grain removal of K in this study was 56% of the total K removed in grain plus straw. According to Tarkalson, et al. (2009), 9.34 kg K_2O tonne^{-1} was removed when removing wheat straw. Compared to N and P, wheat straw contains a greater proportion of K at grain mass nutrient ratios of 0.47, 0.26 and 4.12 of N, P and K, respectively.

Tissue sampling gives an indication of uptake and current nutrient status in soybean. In Kentucky, Coale and Grove (1991) found that K accumulation rate was greatest between R1 (beginning bloom) and R5 (beginning seed) (Fehr and Caviness, 1971) and was typically increased by high K soil fertility conditions (88+ mg K kg^{-1}) by 87 %, compared to low K soil fertility conditions. In Ontario, Yin and Vyn (2004) studied three fertilizer placement methods, two conservation tillage systems, and two soybean row widths to determine the critical K value at R1 for maximum seed yield was 24.3 g kg^{-1}. In that study, KCl applications of 100 kg K ha^{-1} increased soybean leaf concentrations by 5.1 to 8.0 g K kg^{-1}. Clover and Mallarino (2012) determined critical leaf K concentration at R1 to be 17.6 to 20.0 g K kg^{-1} for maximum yield.

There is lack of research in the Mid-Atlantic in K fertility on double-crop, wheat soybean rotations. Due to differences between soils of the Mid-Atlantic and other regions, and due to differences between full-season and double-crop systems, research on the response of soybean to K fertilizer growing under these environments is needed. We hypothesize that maximum soybean yield will be reached at soil K concentrations between 38 to 88 mg K kg^{-1} (medium testing STK) and plant tissue K sufficiency ranges between 17.5 and 25 g K kg^{-1}, according to current Virginia recommendations (Donahue, 2000). The objectives of this study were to determine double-crop response to soil test K and K fertilizer rates on coastal plain or piedmont soils of Virginia. Specifically, we will 1) correlate relative yield, V5 plant K concentration, R2 trifoliate leaf K concentration, and physiological mature wheat stem and chaff K concentration with Mehlich-1-extractable soil K; 2) establish critical tissue K concentrations for V5 and R2 soybean; and 3) calibrate K fertilizer necessary for maximum yield.

Materials and Methods

Fourteen field trials were conducted on soils representative of the Piedmont and Coastal Plain regions of Virginia during 2013 and 2014 (Table 3.1). Maturity group IV or V soybean was planted no-till into harvested wheat in June or July with farmer owned or small plot equipment in 19 or 38-cm rows. Planting dates ranged from June 30 to July 15 for 2013 and 2014. Most test sites followed a two- or three-year crop rotation and previous year’s crop was usually corn or soybean. Sites in Accomack County in 2014 were unique as they were planted to cucumbers and squash in the previous year. This site was located on the Eastern Shore Agricultural Research and Extension Center where produce research is conducted. Cultural practices and pest management followed North Carolina or Virginia Cooperative Extension recommendations. All sites were dependent upon rainfall and no irrigation was used. Rainfall varied with location, but was generally above the 30-year average during June and July of 2013 at all sites except for the two sites in Accomack, which had a deficit of 7.1 cm (Table 3.2). Rainfall was then below average during August and September for all sites except Culpeper and Virginia Beach, where rainfall totals were near average. In 2014, the sites in Accomack experienced similar conditions as in 2013 and Suffolk sites experienced near-normal rainfall in all months except August, when there was an 8.9 cm deficit. Growing season temperatures were near or slightly above average in 2013 and slightly below average in 2014.

At some locations, two adjacent experiments were conducted; wheat straw was either left on the ground or removed by baling or raking. Aboveground wheat biomass samples (1 m^2) were taken in double crop experiments immediately before wheat harvest. These samples were used to determine the amount of K remaining or removed in the straw and the amount of K removed in the grain. Samples were weighed to obtain wet weight and a subsample (1/4 of actual sample weight) was removed from the overall sample. Wheat heads were separated from the stem by cutting at the base of the head. Grain and chaff were separated with a stationary thresher in 2013 or by hand shelling in 2014. Chaff and stem were re-combined for future measurements. All samples were dried at 60 °C then ground using a Wiley Mill grinder with a 0.5 mm screen. Samples were then digested using nitric acid and hydrogen peroxide (EPA 3050B) and analyzed at Virginia Tech soil testing laboratory using inductively coupled atomic plasma mass spectrometry (ICAP).

Within two weeks of soybean planting and before fertilizer was applied, a composite soil sample consisting of an average of 12 subsamples was collected at depths of 0 to 15, 15 to 30, and 30 to 60 cm within each replication. Soil samples were air-dried, ground, and sent to Virginia Tech soil testing laboratory for analysis using Mehlich I extraction procedures, which is the routine method used at that laboratory. Five grams of sieved, air-dried soil were placed into a 150 mL extraction flask, then 25 mL of Mehlich I extracting solution (0.05 *M* H_2SO_4 + 0.05 *M* HCl) was added and shook for 5 minutes on a reciprocating shaker set at a minimum of 180 opm. The sample was filtered through a Whatman no. 2 filter paper and analyzed using ICAP (Helmke and Sparks, 1996). This process was performed for each soil test sample received at the VT laboratory. Table 3.3 lists the average mg K kg^{-1} and standard error for each site at the three sampling depths.

Each experiment was designed as a randomized complete block with four replications. Individual plot size was 3.8 m wide and 14.6 m long. After the soil was sampled, K fertilizer was broadcast by hand on the surface of the soil (not incorporated) at 0, 28, 56, 112, 168, or 224 kg K ha^{-1} using granular muriate of potash (0-0-60). To ensure that other nutrients were non-limiting, fertilizer containing only those limiting nutrients was applied at the same time if needed and plants were monitored for deficiency symptoms other than K throughout the growing season. Wheat was not fertilized with K-containing fertilizers; therefore this was the only K fertilizer used within the last year.

To determine K concentration in the plant, tissue samples were taken at V5 (5th trifoliate) and R2 (full bloom), (Fehr and Caviness, 1977). At V5, samples consisted of 10 plants at random locations from each plot in 2013 and 1 m of row from each plot in 2014. Twenty uppermost, fully developed soybean trifoliate leaves were randomly collected at the R2 stage from each plot in 2013 and 2014. Plant tissue for all V5 plants and R2 leaves were dried at 60^{o} C, then ground using a Wiley Mill grinder with a 0.5 mm screen. Samples were then digested using EPA 3050 B and analyzed using ICAP.

Soybean was harvested at full maturity (R8) after seed moisture approached 130 g H_2O kg^{-1} of seed using a small plot research combine equipped with scale and moisture tester. In 2013, plots were harvested with a 1.2 m-combine head, collecting seed from rows two through four in 30 cm-row tests and rows two through seven in 19 cm-row tests. In 2014, plots were harvested with a 1.5 m-combine head, collecting seed from rows two through five in 38-cm row experiments and rows two through nine in 19-cm experiments. Seed yield was adjusted to 130 g H_2O kg^{-1}.

Data were subjected to analysis of variance using the PROC GLM procedure of SAS. Fixed effects were K fertilizer rates and random effects were replications. A single degree of freedom contrast comparing the yield of soybean receiving no K against the average yield of soybean fertilized with K was performed to classify each site-year as responsive or unresponsive to K fertilization. Yield responses were interpreted as significant at $P < 0.10$.

Soil test K levels were somewhat variable between replications at some sites; therefore, soil test K and relative yields were not averaged over replications to perform regression analysis. To obtain relative yields, the unfertilized controls (0 kg K_2O ha^{-1}) were divided by the highest yielding treatments receiving potassium fertilizer within each replication and multiplied by 100. Linear and quadratic relationships between relative seed yields and soil test K, V5 plant tissue, and R2-stage trifoliate-leaf tissue were defined using the PROC REG procedures of SAS 9.4. The Student's residual (<-2.5 and >2.5) and Cook's D statistics were used to identify outlying and influential observations, respectively. The outlying or influential observations were omitted from the dataset when appropriate and the model refit. Linear-plateau models were also fit to the same data using the PROC NLIN procedure of SAS 9.4. From these relationships, maximum relative yields were defined as 5% less than the predicted maximum for quadratic models or as the maximum value of each dependent variable defined by the predicted plateau of linear or quadratic-plateau models. When applicable, maximum yield definitions were used to identify the critical soil K availability index or tissue K concentration.

Calibration of K rates needed to maximize soybean yield was performed using linear and non-linear regression techniques. Analysis of variance was performed with yield data from each site. The minimum K fertilizer rate to maximize yield were determined by using Fisher's protected LSD at $P < 0.10$. The minimum K fertilizer rate that resulted in maximum yield for each site-year was regressed against the corresponding soil test K. Calibration was also performed with multiple regression techniques that included linear and quadratic terms for the soil test K and K fertilizer rate. For this calibration, relative yields were determined by determining treatment means within each test and dividing the each yield by the highest yielding treatment in the test, then multiplying by 100. A significance level of $P = 0.10$ was used to include or exclude terms from the model.

Results and Discussion

Soil Testing

Soil test potassium (STK) at 0 to 15 cm depth ranged from 30 to 177 mg K kg^{-1} across the 14 sites (Table 3.1). Soil test K concentrations are generally thought to decrease with depth (Fernandez et al., 2008). However, unchanging or greater STK concentrations at deeper depths may indicate the cation exchange capacity (CEC) of sandy textured topsoil is not adequate to hold K nutrients and therefore results in leaching into finer textured and higher CEC soil horizons (Fagaria, 2009; Evanylo, 1991). In our experiments, sites 4, 5, 6, 7, 9 and 10 decreased in STK with increasing depth (Table 3.3). These sites contained relatively high CEC values (4.4 to 9.4 g kg^{-1}) at the 0 to 15 cm sampling depth; therefore, these soils likely allowed K to be maintained and not leached into the subsoil. In contrast, site 1decreased slightly from 94 to 78 mg K kg^{-1} between 15 and 30 cm but then increased to 101 mg K kg^{-1} at the 30 to 60 cm depth. Similarly, STK at site 2 remained relatively unchanged through 30 cm with 83 to 87 mg K kg^{-1} and decreased only slightly to 71 mg K kg^{-1} at the 30 to 60 cm sampling depth. Sites 13 and 14 varied little until 30 cm where STK increased somewhat from approximately 30 mg K kg^{-1} to 41 and 50 mg K kg^{-1}, respectively. Soil test K at the remaining four sites changed little throughout 60 cm. The CEC of these soils was less than 5 g kg^{-1} and varied little between sampling depths; thereby explaining unchanging or increasing STK at greater depths.

Wheat Straw

Wheat yields from 2013 (sites 4 through 9), calculated from the 1 m^2 sample, were much less than 2014 (Table 3.4). Stem and chaff biomass in 2013 yielded 55 % of that in 2014 on average, but grain yield in 2013 averaged only 12 % of that in 2014. Although above average rainfall between physiological maturity and harvest in 2013 (Table 3.2) may have lowered grain test weight, it did not likely lower it to that extent. In 2013, much grain was lost when the mechanical thresher was used and this is probably the reason for the poor grain yield. Therefore, the amount of K removed by the grain per ha is not likely correct. However, the concentration of K in the grain in 2013 ranged from 3.4 to 4.4 g kg^{-1}, nearly 50 % greater than the grain K concentration in 2014 where it ranged from 2.2 to 2.9 g kg^{-1}. Due to greater yield in 2014, the straw and chaff removed 40 % more K per ha than in 2013. Still, the concentration of K in straw and chaff was nearly 30 % greater in 2013. Although there appears to be relationship between K removed in the straw and STK, the relationship within year is minimum (Fig. 3.1).

Soybean Yield

Potassium fertilizer increased soybean yield at only one of the 14 sites (Table 3.5). At that site (site 11 in Accomack), the yield response was quadratic and maximized at 156 kg K_2O ha^{-1} (Fig. 3.2a). In contrast, yield declined in a quadratic manner at site 12 (Fig. 3.2b). Soil test levels at all depths were approximately equal (Table 3.3). Site 11 was planted to cucumbers in the previous year and site 12 was planted to squash. This difference may have affected the response, but it is not likely. Straw was not removed from site 11; therefore, more K should have been available than at site 12, where straw was removed.

Soil test K at the 0 to 15 sampling depth at the two responsive sites was 65 and 56 mg K kg^{-1} at sites 11 and 12, respectively (Table 3.3). The remaining unresponsive sites had STK values from 30 to 177 mg K kg^{-1}, of which two were classified as low, five were classified as medium, and five were classified as high. Yield response is expected in low STK soils, sometimes in medium STK soils and almost never in high STK soils (Donahue, 2000). Therefore, yield response was not expected in the five high STK soils but a positive yield response was expected in the two low STK soils and at least 50 % of the medium STK soils. However, with the exception of site 10, STK remained relatively constant with depth for soils classified as medium. Furthermore, STK increased at the 30 to 60 cm depth at sites 13 and 14, where the soil was classified as low. This could partially explain why there was no response to yield at the low and medium testing sites. In addition, soybean in these experiments was rarely under water stress. Zorb et al. (2014) stated that K plays a prominent role in crop resistance to dought due to its roles in turgor generation, primary metabolism, and long-distance transport. Without at least some intermittent drought stress, lack of adequate STK may not affect yield in as great of an extent. In contrast to these results, studies in Iowa showed positive response to

K_2O fertilizer at four of 10 sites (Clover and Mallarino, 2013) and, in Arkansas on silt loam soils, 21 of 34 sites responded to K_2O fertilizer (Slaton et al., 2010). Soil test K concentrations of the Iowa sites ranged from 41 to 131 kg K ha^{-1} and 41 to 131 mg K ha^{-1} in Arkansas. However, these studies were not conducted under double-crop systems. Furthermore, the lower CEC soils that are prominent in the Coastal Plain and Piedmont regions of Virginia may respond differently to K fertilization than silty loam soils similar to those in Iowa and Arkansas.

Lack of yield response to K_2O fertilizer could also be attributed to variability of STK between replicates in some experiments. Standard errors are listed in Table 3.3 for STK levels at each sampling depth. For example, average STK at site 2 was 83 mg K kg^{-1} with a standard error of 8.34 at 0 to 15 cm. However, compared to the full season standard errors in Chapter 2, this variability was minimal. For instance, site 7 in full season had average STK at 0 to 15 cm of 37 mg K kg^{-1} with a standard error of 14.4.

Still due to some variability among replications at some sites, four unfertilized control relative yields were calculated from each experiment by using the greatest yield within each replication. The corresponding STK values for each replication, along with control plot relative yields were used for regression analysis rather than using relative yields and STK values averaged across replicates to determine soil supply nutrient sufficiency. Relative soybean yield increased at a diminishing rate to a maximum relative yield of 91% at STK of 120 mg K kg^{-1} for straw remaining sites (Fig. 3.3a) and a maximum relative yield of 98% at an STK of 116 mg K kg^{-1} for straw removed sites (Fig. 3.2b) according to the quadratic model. Maximum yield is defined here as the maximum yield predicted minus 5%. Therefore, the critical STK concentration to produce 86% relative yield for straw remaining was 49 mg K kg^{-1} and to produce 93% relative yield for straw removed was 70 mg K kg^{-1} to produce 93% relative yield.

It must be noted that R_2 values indicated that only 5 and 18% of the variability; therefore, there is little confidence in these responses. Although these critical levels are similar to full-season soybean (Chapter 2) where the critical level was estimated to be 88 mg K kg^{-1}, it is not likely accurate since only one of the 14 sites actually responded to K_2O fertilizer. Furthermore, nonlinear regression did not fit these data. The linear portion of the linear plateau model for full-season soybean (Chapter 2) was from 0 to 38.8 mg K kg^{-1}, but only two sites in this study (Table 3.3) had STK in this range. Therefore, the lack of low STK experimental sites in this dataset could also explain why there was little to no soybean yield response to STK.

V5 Tissue Concentration

Total K uptake in K_2O fertilized soybean at the V5 growth stage was greater than the no K_2O fertilizer control in eight of fourteen sites, even though there was not a consistent yield response at six of those sites (Table 3.6). Although a yield response did not always occur, soybean was utilizing soil applied K fertilizer for growth and development. Still, neither the quadratic model nor the linear plateau model fit these data and a critical V5 plant concentration could not be determined (Fig. 3.4). Plant K concentration values at V5 ranged from 23 to 35 and 17 to 36 g K kg^{-1} for straw remaining and straw removed, respectively. Relative yield ranged between 75 and 99%. The plant K concentrations determined in our study are comparable to Sabbe et al.’s (2011) research as our soybean V5 K concentrations (Table 3.6) fall within or above the sufficiency range (15 to 22.5 g K kg^{-1}) for young soybean.

R2 Tissue Concentration

Plant K concentration at R2 responded to K fertilizer at four out of fourteen sites and was almost significant at sites 3 and 7 with P-values of 0.1008 and 0.1075, respectively, (Table 3.7). Sites 8, 10, 13 and 14 had significant increase in K concentration at both V5 and R2 growth stages. However, sites 4, 9 and 12 were significant at V5 but not R2. Neither quadratic nor linear plateau models fit the data when soybean relative yield was regressed against plant K concentration at R2 (Fig. 3.5). There were little to no deficiency symptoms present throughout the 2013 and 2014 soybean seasons. Plant K concentrations for R2 ranged from 13 to 31 or 20 to 28 g K kg^{-1} for straw remaining or straw removed, respectively (Figs. 3.5 a and b, Table 3.7. Critical R2 trifoliate concentration for maximum relative yield of 82% was determined to be 24.6 g K kg^{-1} (Chapter 2, Fig. 2.3) for full-season soybean in Virginia and northeast North Carolina. According to this critical concentration, double-crop R2 samples were sufficient at nine of fourteen sites in at least one treatment (Table 3.7).

Fertilizer 2Calibration

Calibration of K fertilizer rate necessary to achieve highest yield is not included in the results because neither model was significant. There were only two yield-significant sites for the double-crop experiment and therefore not enough data to produce accurate results.

Conclusions

Potassium fertilization increased yield at only one of 14 sites. Although relative yield responded quadratically to STK, the R^2 was very low; therefore, little of the variability in the data could be explained by this relationship. With neither linear nor non-linear models fitting the data, the critical STK concentration at which yield would no longer respond to K fertilizer could not be determined.

Our plant tissue analysis for V5 and R2 did support our hypothesis that no yield decrease would occur if plant K concentration ranged between 17.5 and 25 g K kg^{-1}. The double-crop range of plant K concentration for V5 was between 17 and 35 g K kg^{-1} with the straw removed and between 23 to 35 g K kg^{-1} with straw remaining. Flowering stage (R2) tissue samples revealed that only site 13, where the STK was low, had K concentrations less than 17.5 g K kg^{-1} when no K_2O was applied.

There was sufficient rainfall at most sites in 2013 and 2014, which could have relieved plant stress that is typical in hot, dry summers. There would be less access to soil K, therefore less uptake in drier years. Furthermore, due to lack of stress, K's role in drought resistance was not likely expressed in these experiments. Therefore, 0 to 15 cm sampling depths may not reflect the total amount of K available to soybean and might not be adequate for low CEC soils.

Due to the lack of soybean yield response to K_2O fertilizer, a calibration curve could not be developed with these data. More data is needed, especially at low STK levels and drier environments to complete this research. We plan to conduct research in 2015 at four sites, and hopefully gain responsive data so that a calibration curve can be developed and compared to current Virginia Cooperative Extension recommendations guidelines.

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Table 3.1. Double-crop locations, previous crop, soil types, and soil characterization information from 0 to 15 cm depth for 14 field trials on Piedmont and Coastal Plain soils of Virginia

Site	**Year**	**County/City**	**Straw Removed**	**Previous Year's Crop**	**Soil Texture**	**Classification**	**OM†**	**CEC†**	**pH**	**K**	**P**	**Ca**	**Mg**
							----g kg^{-1}----			**----------mg kg^{-1}----------**			
1	2013	Accomack	No	Fallow	Sandy loam	Typic Hapludults	1.1	4.2	6.4	94	102	490	66
2	2013	Accomack	Yes	Fallow	Sandy loam	Typic Hapludults	0.6	2.4	6.3	83	26	334	56
3	2013	Brunswick	No	Soybean	Sandy clay loam	Typic Kanhapludults	1.4	3.3	5.5	60	73	286	49
4	2013	Culpeper	No	Corn	Fine sandy loam	Typic Hapludults	3.7	9.4	7.3	174	79	1694	63
5	2013	Culpeper	Yes	Corn	Fine sandy loam	Typic Hapludults	3.9	9.3	7.1	177	53	1651	72
6	2013	Mecklenburg	No	Soybean	Fine sandy loam	Typic Kanhapludults	3.4	5.7	6.4	98	14	776	131
7	2013	Mecklenburg	Yes	Soybean	Fine sandy loam	Typic Kanhapludults	2.6	5.2	6.2	152	14	589	107
8	2013	Middlesex	No	Soybean	Loam	Aquic Hapludults	1.2	4.3	6.2	74	37	491	99
9	2013	Middlesex	Yes	Soybean	Loam	Aquic Hapludults	1.7	6.1	6.1	76	27	458	97
10	2013	Virginia Beach	Yes	Corn	Sandy loam	Typic Endoaqualfs	2.4	8.6	6.1	51	39	1070	169
11	2014	Accomack	No	Cucumbers	Sandy loam	Typic Hapludults	0.9	4	6.5	65	56	549	71
12	2014	Accomack	Yes	Squash	Sandy loam	Typic Hapludults	0.9	3.7	6.5	56	62	533	62
13	2014	Suffolk	No	Corn	Sandy loam	Arenic Hapludults	1.1	2.6	5.9	30	54	307	61
14	2014	Suffolk	Yes	Corn	Sandy loam	Arenic Hapludults	1.1	2.6	5.8	30	40	323	52

†OM, organic matter; CEC, estimated cation exchange capacity

Table 3.2. Average monthly temperature (°C) and rainfall (cm) obtained from closest weather station to each double-crop site. Surplus or deficit of rainfall, compared to 30-year average, is listed in parentheses.

Site(s)	Location	May	June	July	August	September	October
1, 2	**Accomack**						
	Rain	2.3 (-6.1)	9.5 (-0.5)	6.2 (-6.6)	7.1 (-3.8)	2.7 (-7.3)	10.2 (1.1)
	Temp	19.4 (0.8)	24.3 (0.8)	27.4 (1.5)	24.3 (-0.6)	20.7 (-0.9)	18.9 (2.9)
4, 5	**Culpeper**						
	Rain	8.0 (-2.6)	24.7 (14.4)	20.0 (11.6)	9.7 (1.9)	12.8 (1.4)	8.8 (0.8)
	Temp	17.7 (0.8)	23.2 (1.4)	25.6 (1.6)	23.7 (0.4)	20.7 (1.5)	16.2 (2.8)
3,6,7	**Brunswick, Mecklenburg**						
	Rain	3.1 (-6.3)	16.8 (7.0)	14.5 (2.4)	3.0 (-8.7)	3.4 (-7.5)	4.0 (-3.5)
	Temp	17.6 (-1.1)	24.2 (0.7)	26.1 (0.7)	24.0 (-0.4)	21.1 (0.4)	16.3 (1.7)
8,9	**Middlesex**						
	Rain	7.2 (-3.3)	20.6 (11.6)	13.7 (2.1)	9.8 (-2.0)	2.6 (-8.1)	5.7 (-3.1)
	Temp	18.6 (-0.7)	23.8 (-0.1)	26.1 (0.1)	24.3 (-0.8)	20.8 (-0.6)	16.8 (1.3)
10	**VA Beach**						
	Rain	4.5 (-4.0)	4.5 (-6.0)	24.9 (12.3)	5.9 (-7.2)	16.8 (6.4)	3.0 (-5.7)
	Temp	23.0 (4.2)	25.6 (2.0)	26.9 (0.8)	26.1(0.9)	24.5 (2.4)	19.0 (2.5)
11,12	**Accomack**						
	Rain	11.8 (3.4)	5.4 (-4.6)	8.3 (-4.5)	5.6 (-5.3)	10.1 (0.1)	3.4 (-5.8)
	Temp	18.6 (0.0)	22.1 (-1.4)	23.7 (-2.2)	22.4 (-2.4)	20.7 (-0.9)	15.8 (-0.2)
13, 14	**Suffolk**						
	Rain	6.6 (-3.2)	8.8 (-2.3)	16.1 (3.0)	5.6 (-8.9)	15.3 (1.8)	3.1 (-6.1)
	Temp	20 (0.7)	23.1 (-0.8)	24.1 (-1.9)	23.2 (-1.8)	21.65 (-0.2)	16.1 (-0.2)

Table 3.3. Average Mehlich-I extractable K, standard error and estimated CEC at three sampling depths for 14 sites of double-crop soybean studies in Piedmont and Coastal Plain of North Carolina and Virginia

Site	**Year**	**County/City**	**Straw Removed**	**0-15 cm**		**15-30 cm**		**30-60 cm**	
				CEC†	**Soil K ‡**	**CEC†**	**Soil K ‡**	**CEC†**	**Soil K ‡**
				g kg^{-1}	mg K kg^{-1}	g kg^{-1}	mg K kg^{-1}	g kg^{-1}	mg K kg^{-1}
1	2013	Accomack	No	4.2	94 ± 5.5	3.8	78 ± 3.4	4.2	101 ± 7.6
2	2013	Accomack	Yes	2.4	83 ± 8.3	2.8	87 ± 3.4	2.8	71 ± 2.9
3	2013	Brunswick	No	3.3	60 ± 1.3	3.1	59 ± 5.8	5.8	64 ± 4.6
4	2013	Culpeper	No	9.4	174 ± 3.9	6.3	90 ± 1.7	5.1	50 ± 6.3
5	2013	Culpeper	Yes	9.3	177 ± 3.0	6.3	76 ± 4.1	4.8	49 ± 0.8
6	2013	Mecklenburg	No	5.2	98 ± 3.9	4.9	48 ± 6.4	5.3	37 ± 9.9
7	2013	Mecklenburg	Yes	5.7	152 ± 8.1	4.3	115 ± 4.0	3.7	78 ± 3.5
8	2013	Middlesex	No	4.3	74 ± 3.7	3.8	66 ± 2.3	4.6	67 ± 1.7
9	2013	Middlesex	Yes	4.4	76 ± 6.3	3.9	66 ± 2.3	4.8	58 ± 3.7
10	2013	Virginia Beach	Yes	8.6	51 ± 1.9	5.8	21 ± 0.9	4.7	16 ± 0.3
11	2014	Accomack	No	4.0	65 ± 3.7	4.2	75 ± 5.5	4.1	73 ± 2.7
12	2014	Accomack	Yes	3.7	56 ± 0.5	3.7	66 ± 1.6	3.9	72 ± 2.3
13	2014	Suffolk	No	2.6	30 ± 2.1	1.9	33 ± 4.2	1.8	41 ± 3.4
14	2014	Suffolk	Yes	2.6	30 ± 2.1	1.5	28 ± 2.0	1.6	50 ± 6.9

† CEC – estimated Cation Exchange Capacity

‡ Soil K concentration, mg K kg^{-1} ± Standard Error

Table 3.4. Wheat grain yield, stem and chaff biomass and K removal at 10 double-crop sites in Virginia

Site	**Soil**	**Grain Yield**	**Grain K Uptake**	**Stem + Chaff Biomass**	**Stem + Chaff K Uptake**
	---mg K kg^{-1}---	--kg ha^{-1}--	--kg K ha^{-1}--	---- kg^{-1} K ----	----kg K ha^{-1}----
4,5†	175	645.5	2.4	3918.9	47.7
6	98	950.2	4.2	4696.3	32.0
7	138	756.6	2.6	4586.2	50.8
8,9†	75	1252.3	4.7	5482.9	45.7
11	65	7803.6	18.4	7766.1	64.3
12	56	8253	18.5	8819.9	74.1
14	65	8040.8	23.2	9763.8	66.6
15	30	6005.6	14.8	7503.9	37.8

† Sites 4,5 and 8,9 were within the same field; therefore only one sample was collected.

Table 3.5. Double-crop soybean actual and relative yields as affected by K fertilizer rate at 19 site years on Coastal Plain and Piedmont soils of Virginia.

		K_2O Fertilizer Rate, kg ha^{-1}							
Site No.	RY†	0	28	56	112	168	224	Sdf ‡	LSD
	-%-	-------------------------------kg ha^{-1}-------------------------------						Pr>F	kg K ha^{-1}
1	90	2885	3096	2909	2894	2672	2541	0.691	NS§
2	89	2488	2570	2362	2540	2441	2579	0.9009	NS
3	93	2242	2158	2302	2183	2290	2164	0.7898	NS
4	91	2719	2830	2427	2658	2725	2516	0.6279	NS
5	92	2919	2905	2949	2943	2878	2964	0.925	NS
6	82	1959	2091	2248	2076	2190	1787	0.4355	NS
7	91	2170	2178	2185	2128	2249	1966	0.8324	NS
8	93	2573	2604	2533	2470	2493	2547	0.5336	NS
9	95	2761	2752	2761	2770	2729	2739	0.8832	NS
10	94	3378	3373	3332	3302	3302	3304	0.7153	NS
11	80	3025	3310	3494	3503	3237	3531	0.0299	462
12	99	3311	3229	2998	2815	2958	2908	0.0213	290
13	82	2470	2454	2595	2549	2626	2547	0.7453	NS
14	78	1641	1833	1760	1805	1731	1734	0.5032	NS

† RY, relative yield of soybean receiving no K fertilizer compared to maximum numerical yield of soybean receiving K fertilizer

‡ sdf, single-degree-of-freedom contrast P value comparing the yield of soybean receiving no K to the yield of soybean receiving K

§ NS, not significant (*P*>0.10)

Table 3.6. Mean actual whole plant K concentration at V5 growth stage of double crop soybean as affected by K fertilizer rates at 14 sites on Piedmont and Coastal Plain soils of Virginia.

	K_2O Fertilizer Rate, kg ha^{-1}							
Site	**0**	**28**	**56**	**112**	**168**	**224**	**Sdf†**	**LSD**
	----------------g K kg^{-1}----------------						Pr>F	g K kg^{-1}
1	32.4	32.6	31.2	30.3	30.9	31.8	0.2933	2.1
2	26.9	24.5	25.7	26.2	23.9	26.1	0.3055	3.5
3	24.0	24.1	23.8	26.1	27.0	28.3	0.0500	1.9
4	33.0	33.6	33.8	32.7	33.2	32.5	0.9221	2.5
5	35.6	33.8	34.6	33.7	32.9	32.4	0.0925	2.7
6	27.8	27.0	27.1	27.7	26.9	25.5	0.3319	2.2
7	29.9	30.5	30.3	30.2	30.8	30.0	0.3869	1.3
8	32.2	32.9	33.1	33.7	34.6	32.6	0.0800	1.5
9	28.8	33.4	32.2	32.0	31.8	33.0	0.0006	1.9
10	17.6	19.6	20.2	20.9	20.4	21.6	0.0211	2.6
11	24.8	24.1	23.4	25.6	24.4	25.4	0.9077	3.0
12	19.5	22.3	20.6	24.1	23.1	23.5	0.0777	3.9
13	24.3	29.0	28.9	32.8	31.1	31.4	<.0001	2.8
14	22.1	28.6	29.7	30.0	31.8	33.7	<.0001	3.0

† sdf, single-degree-of-freedom contrast P value comparing the yield of soybean receiving no K to the yield of soybean receiving K

Table 3.7. Mean actual trifoliate K concentrations at R2 growth stage of soybean as affected by K fertilizer rates on Coastal Plain and Piedmont soils of Virginia.

	K_2O Fertilizer Rate (kg ha^{-1})							
Site	**0**	**28**	**56**	**112**	**168**	**224**	**Sdf†**	**LSD**
	----------------g K kg^{-1}----------------							
1	25.8	26.2	25.9	26.2	27.1	26.1	0.6428	2.4
2	22.5	22.3	23.3	24.1	24.3	22.7	0.2529	1.6
3	28.2	28.0	29.1	30.5	30.8	31.1	0.1008	2.2
4	28.1	28.0	28.3	27.9	28.1	28.0	0.9538	0.9
5	26.3	27.1	27.8	26.6	26.7	26.9	0.2059	1.2
6	26.8	27.6	26.7	27.8	26.5	27.8	0.6187	2.2
7	27.9	26.7	26.4	26.4	27.0	26.6	0.1075	1.7
8	19.0	24.4	22.8	24.2	21.7	23.7	0.0134	3.5
9	20.4	20.7	20.7	20.3	21.5	22.3	0.3619	1.6
10	22.3	23.8	23.1	25.1	26.0	27.9	0.0172	2.4
11	21.1	23	20.8	21.9	22.3	21.7	0.4884	2.7
12	19.7	21.6	21.4	21.1	20.1	21.4	0.1934	2.3
13	13.2	19.7	20.7	22.0	22.0	22.6	0.0019	4.9
14	20.4	22.1	22.3	25.8	24.8	25.7	0.0037	2.5

† sdf, single-degree-of-freedom contrast P value comparing the yield of soybean receiving no K to the yield of soybean receiving K

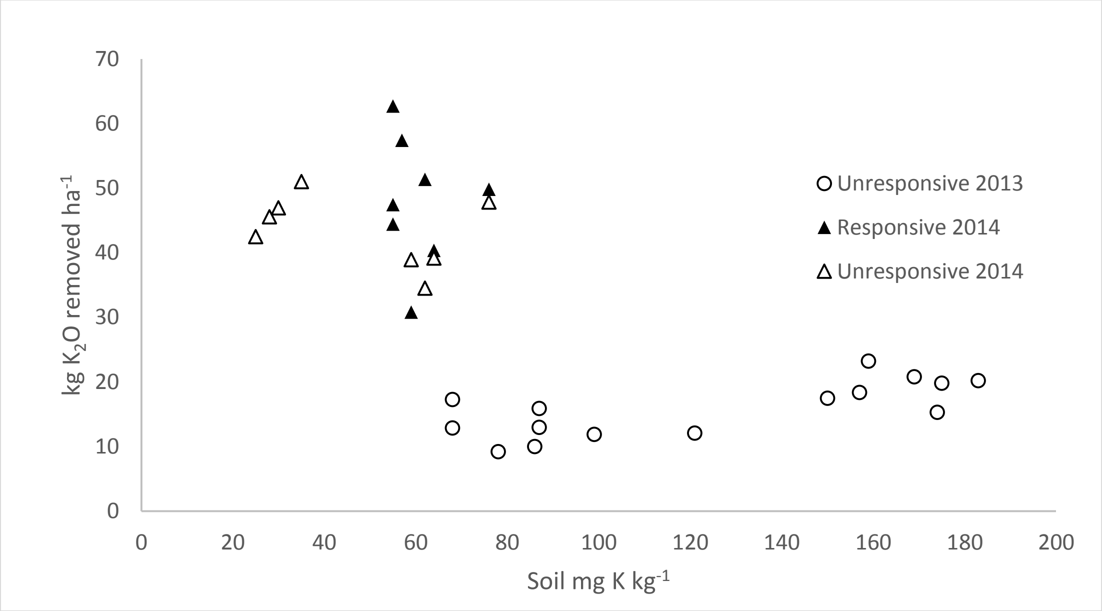

Figure 3.1. Wheat K removal of K_2O in straw and chaff based on STK level. The classification of a site as responsive ($P < 0.10$) and non-responsive sites ($P > 0.10$) was based on single degree of freedom contrasts that indicate whether yield of fertilized plots was different than that of non-fertilized control.

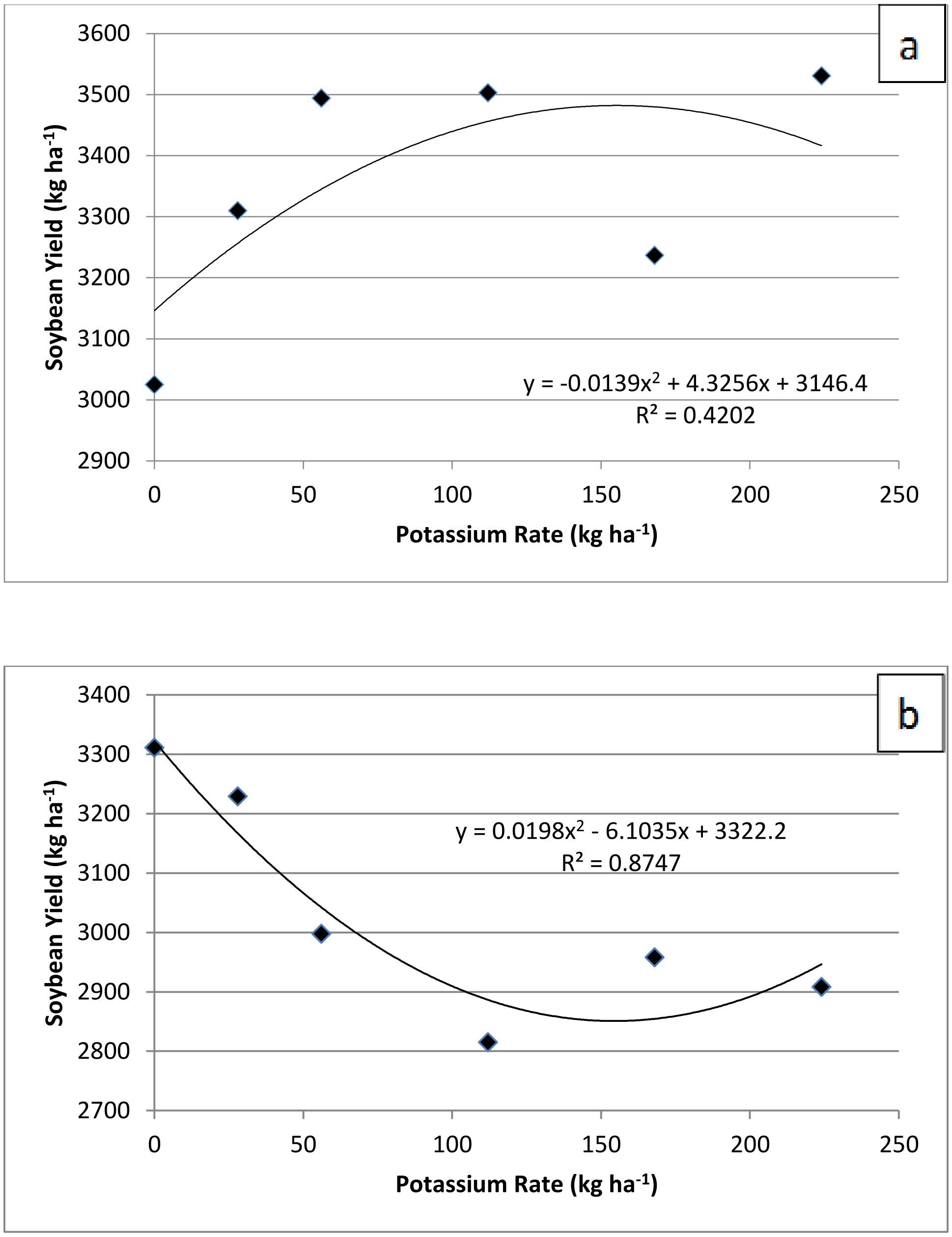

Figure 3.2. Soybean yield response to potassium application rate as predicted with a quadratic model at $P < 0.001$ for sites 11 (a) and 12 (b).

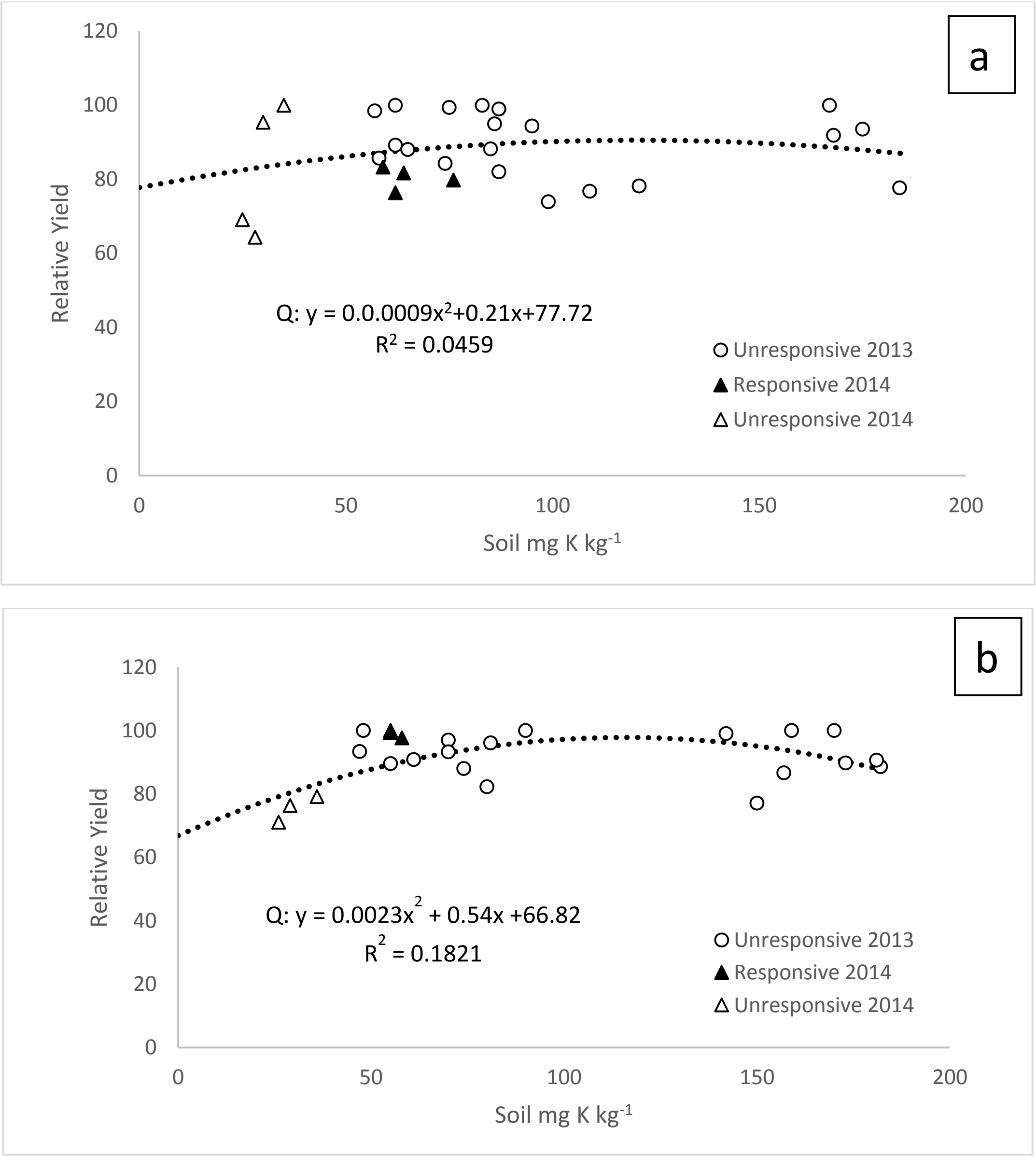

Figure 3.3. Relative soybean yield of straw remaining (a) or removed (b) for each replication regressed against Mehlich-1 extractable soil K as predicted with a quadratic model. Nonlinear regression was not significant for either data set. The classification of a site as responsive ($P < 0.10$) and non-responsive sites ($P > 0.10$) was based on single degree of freedom contrasts that indicate whether the yield of fertilized plots was different from the non-fertilized control.

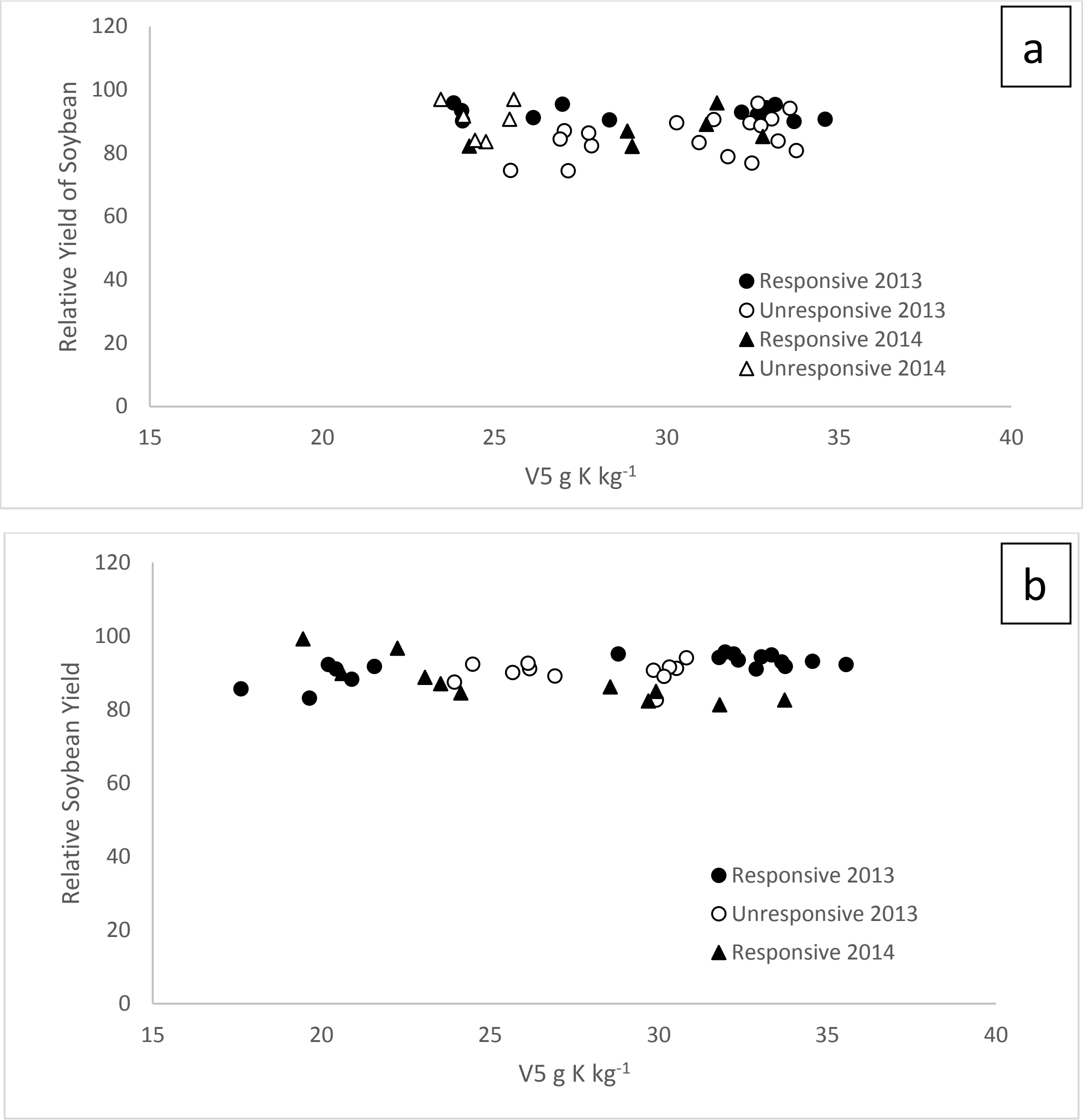

Figure 3.4. Relative soybean yield of straw remaining (a) or removed (b) for each replication averaged across treatments versus V5 K. Neither quadratic, linear nor nonlinear models were significant. The classification of a site as responsive ($P < 0.10$) and non-responsive sites ($P > 0.10$) was based on single degree of freedom contrasts that indicate whether the V5 concentration of fertilized plots was different from the non-fertilized control.

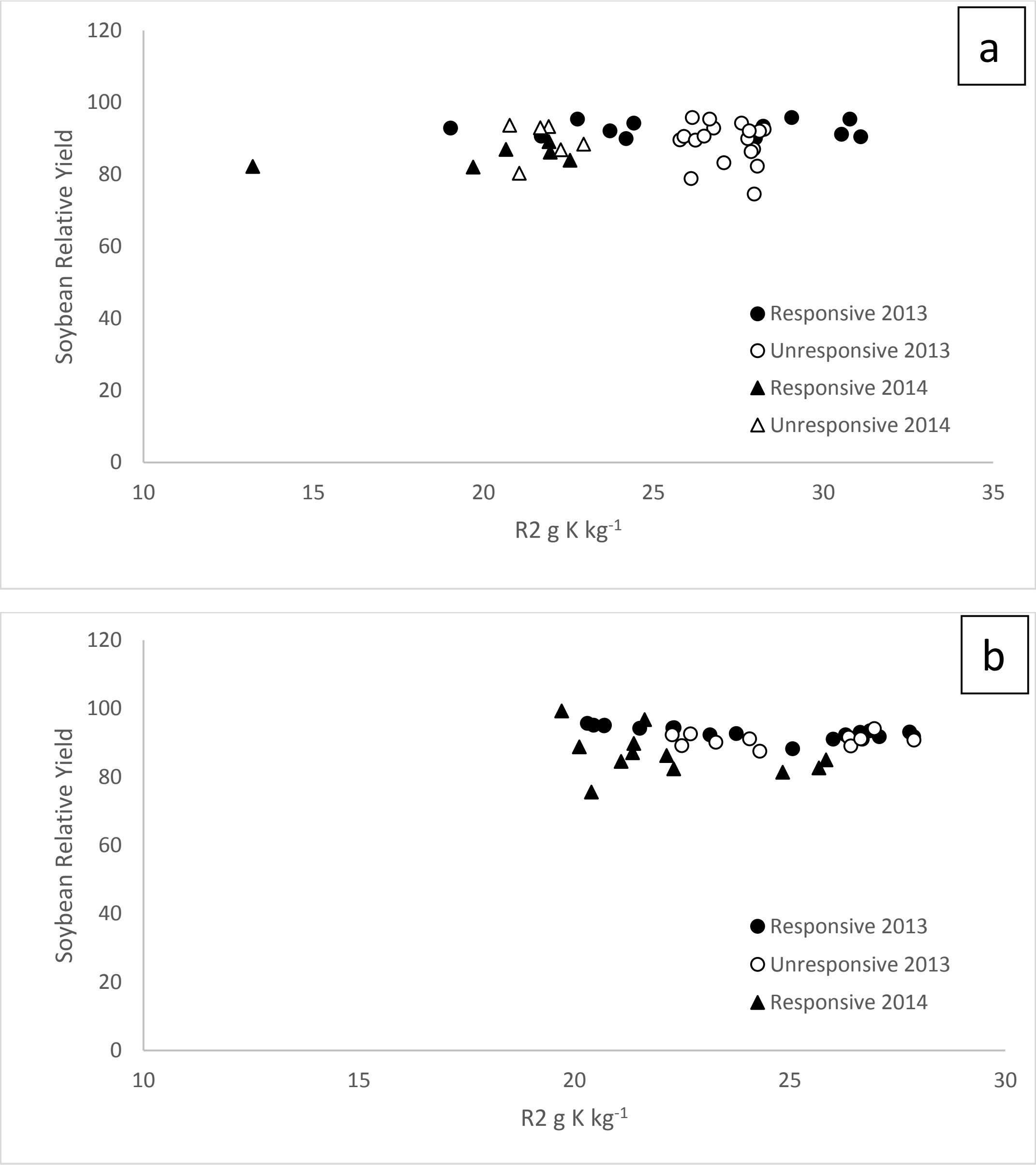

Figure 3.5. Relative soybean yield of straw remaining (a) or removed (b) for each replication versus R2 K. Neither quadratic, linear nor nonlinear models were significant. The classification of a site as responsive ($P < 0.10$) and non-responsive sites ($P > 0.10$) was determined from single degree of freedom contrasts that indicate whether the R2 concentration of fertilized plots was different from the non-fertilized control.

Chapter 4 – Comparison of different soil preparation methods prior to analysis compared to air-dried soil preparation currently used in Virginia.

Abstract

Soil testing is necessary in order to determine soil nutrient status for soybean [*Glycine max.* (L.) Merr.] nutrient management. Soil sample preparation methods may potentially influence the amount of exchangeable K based on the method of preparation used prior to soil analysis. Composite soil samples were taken from each replication in 12 full-season field trials, prior to potassium fertilization in 2014 to determine differences in extractable K using four methods (field moist, oven dried, air dried, and air dried followed by oven drying) of preparing the soil for analysis with Mehlich-1 extractant. Samples were mixed and split for field moist and air-dry conditions. There were site and drying method differences as well as a site by drying method interaction. One or more of the alternative soil drying methods were significantly different from air drying, which is used by Virginia Tech soil testing laboratory at eight of 12 sites, however, only in two of the eight sites did air-dry differ from moist soil samples by 2.4 and 10.3 mg Kg kg^{-1}. These data indicated that current preparation methods for soil analysis is sufficient in Virginia for low to medium k testing sandy loam soils.

Introduction

Soil testing is an important aspect of plant nutrient management and can help growers determine levels of available nutrients within a field and the amount of fertilizer needed. In soybean [*Glycine max.* (L.) Merr.], potassium is one of the most important soil nutrients for plant growth and development. Potassium improves water and nutrient uptake by increasing root growth; builds cellulose, which reduces lodging; is as an enzyme activator; reduces respiration; and prevents energy loss from the plant (Fagaria, 2009). Throughout Virginia, Mehlich-1 extractant is typically used to determine plant-available K. Most soil samples are taken as a field composite sample representing a field or part of a field and sent to a soil testing lab for analysis. At the lab they are first air-dried, then five grams of sieved, air-dried soil are placed into a 150 mL extraction flask, and then 25 mL of Mehlich I extracting solution (0.05 M H_2SO_4 + 0.05 M HCl) is added and shook for 5 minutes on a reciprocating shaker set at a minimum of 180 opm. The sample is filtered through a Whatman no. 2 filter paper and analyzed using inductively coupled plasma spectrometry (Helmke and Sparks, 1996).

It is thought that air drying and oven drying can change the soil composition and in turn, have a negative influence on actual K extractable form in soil solution. When dried, the amount of exchangeable K on the soil test report can be greater than the amount of K actually available and in turn, can lead to lower than necessary fertilizer recommendations (Attoe, 1946, Grava et al., 1961, Barbagelata and Mallarino, 2012). Field moist conditions present a more accurate exchangeable K concentration and it is suggested to be a more efficient method of analysis (Attoe, 1946, Grava et al., 1961, Barbagelata and Mallarino, 2012). The effects of drying soil before analysis were researched in the north central region of the United States, as well as in Wisconsin and Iowa.

Air-drying is typically used when drying soils in laboratories because the oven heat is thought to affect nutrient availability by increasing exchangeable K content when the actual level is less (Grava et al., 1961). Further research by Bray and DeTurk (1939) concluded that heating soils to 200°C increased exchangeable K content when the actual value was less and decreased exchangeable K content when the actual value was greater. Attoe and Truog (1946) developed an equation ($\log Y = k \log X + c$), on a Spencer silt loam, found that the amount of K fertilizer applied, along with air drying at room temperature, was related to the amount of remaining exchangeable K as determined by the equation. Y represented the amount of exchangeable K remaining, X represented the amount of K applied, and k and c were constants determined by the extent of fixation. Exchangeable K increased from 21 to 57 kg ha^{-1}, as a result of drying on an unfertilized Miami silt loam soil soils that were extruded prior to oat planting (Attoe, 1946). Relative humidity levels of 10 to 90% had no K fixation while 100% relative humidity had 42% fixation in dried soils at 10% humidity on a Spencer silt loam (Attoe, 1946).

Grava et al., (1961) studied Nicollet clay loam under three conditions: field moist samples were placed in sealed plastic bags and refrigerated at 3° C until analysis; samples were air dried at room temperature for seven days; and samples were dried in an oven at 105° C for 24 hours. Exchangeable potassium was determined using 1 N ammonium acetate for each drying condition. There was an increase in exchangeable K in both air and oven dried samples, when compared to field moist samples. Samples that had no K fertilizer applied in the field had greater increases than samples with 109 or 218 kg K_2O ha^{-1} fertilizer. Average percentage of increase for treatments of 0, 109 or 218 kg K_2O ha^{-1} were 36.5, 31.0 and 14.2 %, respectively, after air drying and 55.1, 42.9 and 23.7 %, respectively, after oven drying. Samples were taken throughout the growing season and exchangeable K content decreased in field moist soils as the season progressed, regardless of fertilizer treatment, due to plant uptake and utilization of soil nutrients. Grava, et al. stated that there might have be more difference in air drying and oven drying if the soil moisture was at the critical value of 5% or lower. According to Luebs et al., there is little increase in Iowa soil exchangeable K until the moisture level dropped to 5% or lower.

More recently, Barbagelata and Mallarino (2012) performed a field correlation of K soil test methods based on dried and field moist samples in corn [*Zea mays* (L.) Merr.] and soybean in Iowa. Samples were stored at 5°C from two to 10 weeks in plastic bags and sieved through a 5-mm mesh. Subsamples were taken and prepared for drying and analysis. One subsample remained moist and the other was dried at 35 to 40°C. Both samples were analyzed with ammonium acetate and K measured by atomic absorption spectrometry. Oven dried soil samples of non-fertilized soil averaged 145 mg K kg^{-1} and ranged from 56 to 388 mg K kg^{-1} whereas moist soil samples averaged 76 mg K kg^{-1} and ranged from 30 to 356 mg K kg^{-1}. The average K level for oven dried soils was 1.92 times greater than that for moist soils.

Midwest research on silty loam soils indicated that moist soil analysis using ammonium acetate gives a more accurate explanation of soil available K. However, soils of the coastal plain and piedmont of Virginia are very different in properties and textures. Surface horizons are not as deep and low CEC predominates. Drainage will vary from excessively well drained to poorly drained. Although the effects of drying soil before analysis have been researched in the north central region of the United States, no research comparing wet and dry soil analysis of K has been performed in the Mid-Atlantic region of the U.S.A. The objectives of this research is to determine differences in extractable K using four methods of preparing the soil for analysis with Mehlich-1 extractant: 1) field moist; 2) oven dried; 3) air dried; and 4) air dried followed by oven drying.

Materials and Methods

Within two weeks of soybean planting and before fertilizer was applied, a composite soil sample consisting of an average of 12 subsamples at 0 to 15 cm was taken. Samples were mixed and separated into four subsamples. The first subsamples were stored in plastic bags and refrigerated at 5°C to maintain moisture until extracted. The second set of subsamples were dried at 105°C for 24 h. Another set of subsamples were dried in a forced air drying cabinet at 25°C for 24 h. Finally, the last subsamples were dried in a forced air drying cabinet at 25°C for 24 h then oven-dried at 105°C for 24 h. All samples were weighed again after drying to establish soil moisture content (Gardner, 1986). Dried soils were ground to pass a 2-mm sieve using a hammer mill. Samples were extracted by placing 5 g of soil and 20 mL of Mehlich-1 extraction solution into a 60 mL straight walled plastic extraction beaker and shaking for 5 min at 180 opm (Helme and Sparks, 1996). Supernatant was filtered through Whatman 2 filter paper and analyzed using s inductively coupled plasma spectrometry. This process was performed for each soil test sample received at the VT laboratory. Moist and air-dried soil samples were corrected to a dry soil weight equivalent prior to statistical analysis while oven dried samples were assumed to be devoid of moisture.

Analysis of variance was performed to determine differences in soil preparation method and means were separated with Fisher's Protected LSD ($P<0.05$).

Results and Discussion

Statistical Analysis

Analysis of variance revealed site and drying method differences and a site by drying method interaction, therefore data are presented by site. One or more of the alternative soil drying methods were significantly different from air drying, which is used by most soil testing laboratories, at 8 of 13 sites (Table 4.1). Only at two of the 12 sites did air-dry differ from moist soil samples. This difference was only 2.4 mg K kg^{-1} at site 13, a difference that would not likely affect K recommendations. At site 8, the field moist sample extracted 10.3 mg kg^{-1} more K than air-dried from the sample. With this difference K fertilizer recommendations would still not be altered (Table 4.2). Considering that moist and air dried samples at 10 of the 12 sites were not different, there appears to be little reason to alter soil preparation methods in Virginia.

Air-dry then oven-dry

When air-dried soils were further dried in the oven, STK from sites 15, 16, and 18 increased by 11.3, 5.8, and 6.2 mg K kg^{-1} soil. Relative to the soil test values, this represents a 2.2, 2.7, and 17.9% difference. Still, such minor differences are not likely to alter soil K recommendations substantially. In addition, 9 of the 12 sites that were oven dried after air drying were not different from air drying. Therefore, oven drying after air drying appears to have little effect on STK.

Field moist then oven-dry

When field moist soils were dried in the oven, STK from sites 8, 12, 13, 14, and 19 decreased compared to air-dry by 3.4, 44.3, 33.8, 10.5 and 11.7% difference. However, sites 15 and 16 actually increased by 12.8 and 25.3%, as compared to air-dry. These samples were taken on the same day but there is no other explanation for why these two significant sites increased rather than decreased when dried in the oven. Regardless, these differences still did not alter the classification of STK level (Table 4.2).

Variation among methods

Oven-dried samples had the greatest variation from air dried only soils; with six of 13 sites differing (Table 2). Sites 12, 13, and 16 had the greatest variation between the drying methods, relative to STK. Site 12, had an STK level of 14.9 mg K kg^{-1} using the air-dried method but only 8.3 mg K kg^{-1} using the field moist then oven-dried method, a 44% drop in STK. Sites 13 experienced a 34% drop in STK when the oven-dried method was used. In contrast, site 16, had an air-dried STK of 27.3 mg K kg^{-1} compared to a field moist then oven-dried STK of 37.7 mg K kg^{-1}, a 25% increase. Differences at the other significant sites ranged from 11.7% less to 12.8% more STK with the oven-dried samples.

Conclusion

Eight out of 12 sites differed when comparing field moist and oven dried samples to air dried samples. Differences occurred most often when the air-dried was compared to the oven-dried method. Differences were in both low and medium STK levels and although some differences were seen, only one response pushed soil levels into a different category. Regardless, differences in the preparation methods were of little practical importance, as such differences would not have changed K fertility recommendations substantially.

Although more research may be needed on other Mid-Atlantic soil types and STK levels, this research indicated that the current method of air drying soils used by the Virginia Tech soil testing laboratory is adequate and the other methods tested would not generally impact results for low and medium testing Coastal Plain soils.

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Table 4.1. Analysis of K fluctuation under four soil drying conditions and analysis using Mehlich-1-extractant solution. Soil samples were collected in May within 2 weeks of soybean planting.

Site	Location	Soil Series and Type	Classification	O.M.†	C.E.C.†	pH	Field Moist	Field Moist Then Oven-dried	Air Dried	Air-Dried Then Oven-Dried	Pr>f‡	LSD
				---------g K kg^{-1}-----			-------------------mg K kg^{-1}----------------					
8	Chesapeake, VA	Chesapeake SL	Typic Hapludults	1.8	5.3	5.4	48.5	36.9	38.2	40.8	0.0052	5.7
9	Currituck, NC	Bojac LS	Typic Hapludults	1.7	4.8	5.2	81.4	80.2	77.3	84.3	0.1381	NS§
10	Gates, NC	Goldsboro FSL	Aquic Paleudults	1.0	3.4	6.4	48.4	45.3	47.4	59.5	0.2537	NS
11	Gates, NC	Bladen L	Typic Albaquults	0.9	2.4	5.6	39.7	38.2	38.2	31.7	0.6049	NS
12	Lunenburg, VA	Appling SL	Typic Kanhapludults	3.3	5.2	6.3	15.0	8.3	14.9	15.4	0.0001	2.2
13	Mecklenburg, VA	Cecil FSL	Typic Kanhapludults	2.0	4.6	6.7	17.8	10.2	15.4	16.1	<.0001	2.0
14	Mecklenburg, VA	Helena FSL	Aquic Hapludults	1.3	2.8	5.4	17.8	16.2	18.1	18.6	0.0366	1.6
15	Northumberland, VA	Sassafras FSL	Aquic Hapludults	1.7	4.6	6.8	67.4	77.7	68.9	80.2	0.0009	5.4
16	Richmond, VA	Dogue FSL	Typic Endoquults	1.4	2.2	5.3	30.9	37.7	30.1	35.9	0.0084	4.4
17	Suffolk, VA	Emporia FSL	Typic Hapludults	0.8	2.2	5.6	22.6	21.0	21.0	22.3	0.2597	NS
18	Virginia Beach, VA	Dragston FSL	Aeric Endaquults	3.3	5.5	5.7	32.2	26.3	27.3	33.5	0.0332	5.3
19	Westmoreland, VA	Suffolk SL	Typic Hapludults	1.9	4.3	6.4	51.7	46.7	52.9	54.3	0.0060	3.7
	Mean						39.4	35.3	40.7	37.3		

† OM, organic matter; CEC, cation exchange capacity

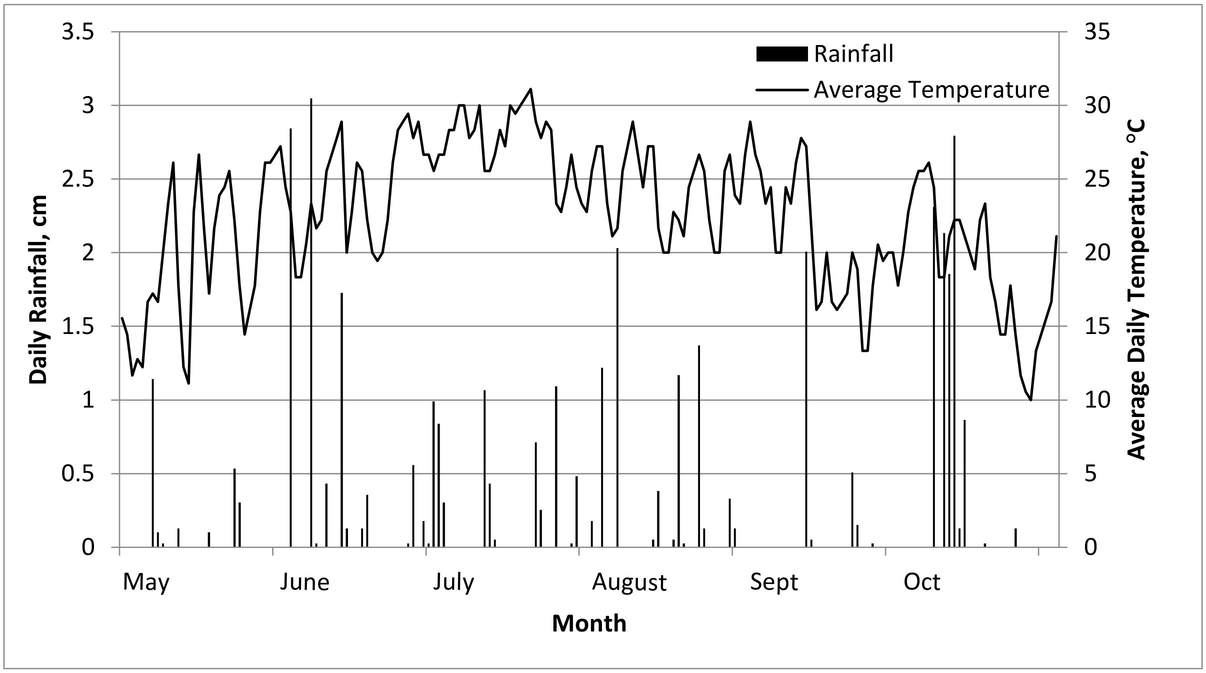
‡ P value comparing STK levels

§ NS, not significant (*P*>0.05)

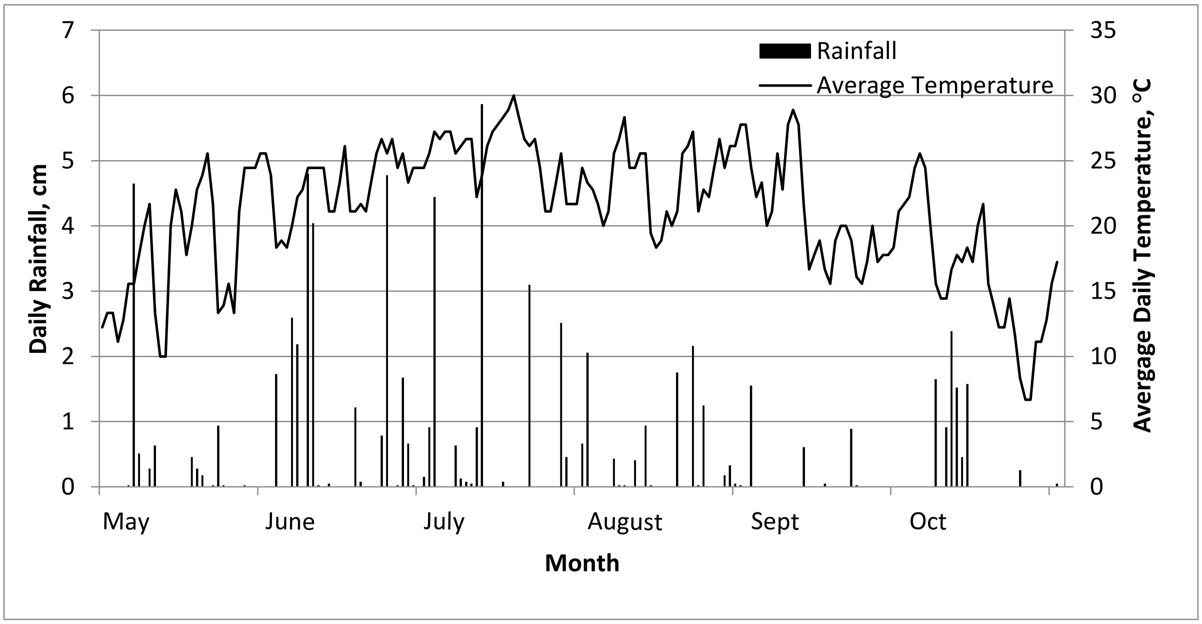
Table 4.2. Virginia Tech soil test levels (mg K kg-1) and current fertilizer recommendations for potassium (K_2O) fertilizer

K Rating	Soil K	Fertilizer Recommendation
	--mg K kg^{-1}--	---kg K_2O ha^{-1}---
L-	0-8	89.6-134
L	9-28	
L+	28-38	
M-	38-50	44.8-89.6
M	51-75	
M+	76-88	
H-	88-105	22.4-44.8
H	106-140	
H+	141-155	
VH	155+	

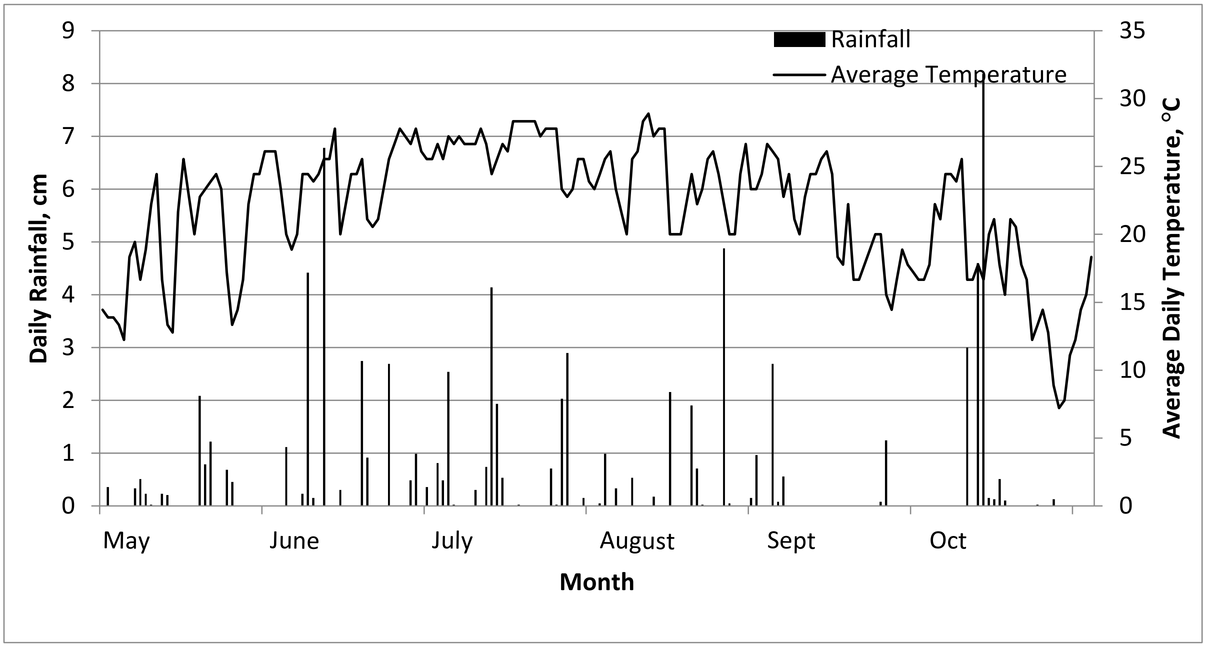
APPENDIX A. Daily rainfall and temperature of 2013 and 2014 full-season and double-crop sites in North Carolina and Virginia



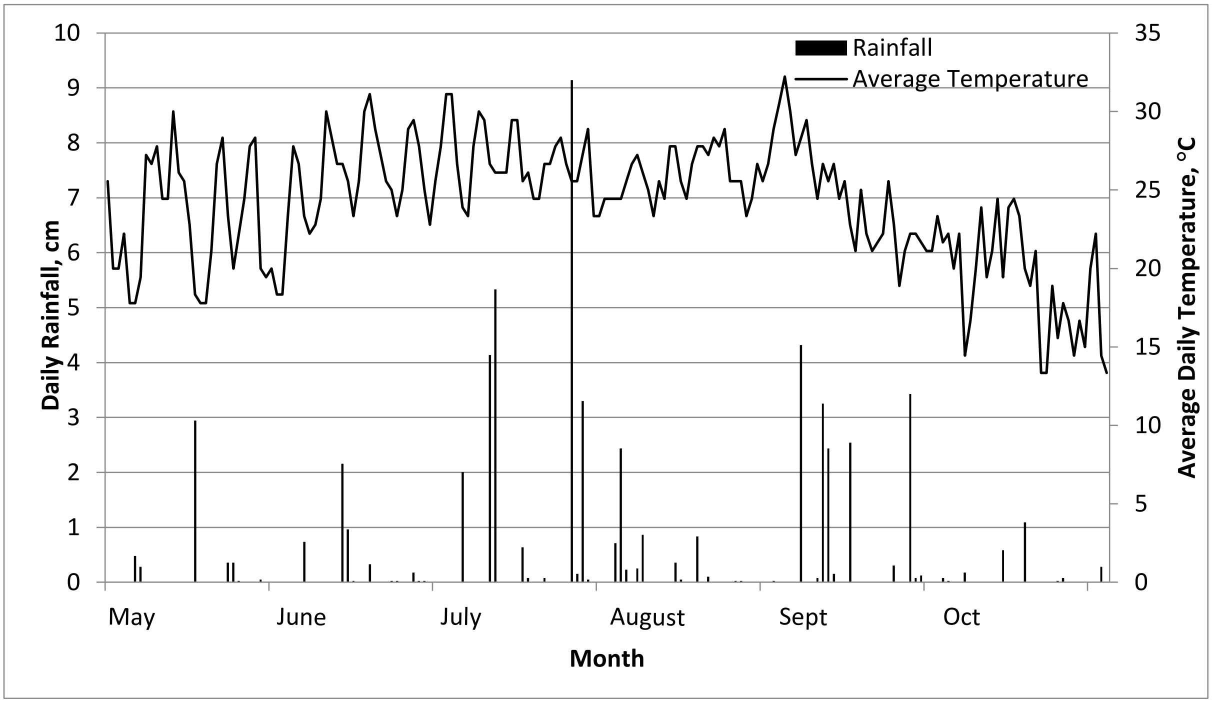
A. 1. Full-season site 1 and double-crop sites 1 and 2 daily rainfall, cm, and average temperature, °C.



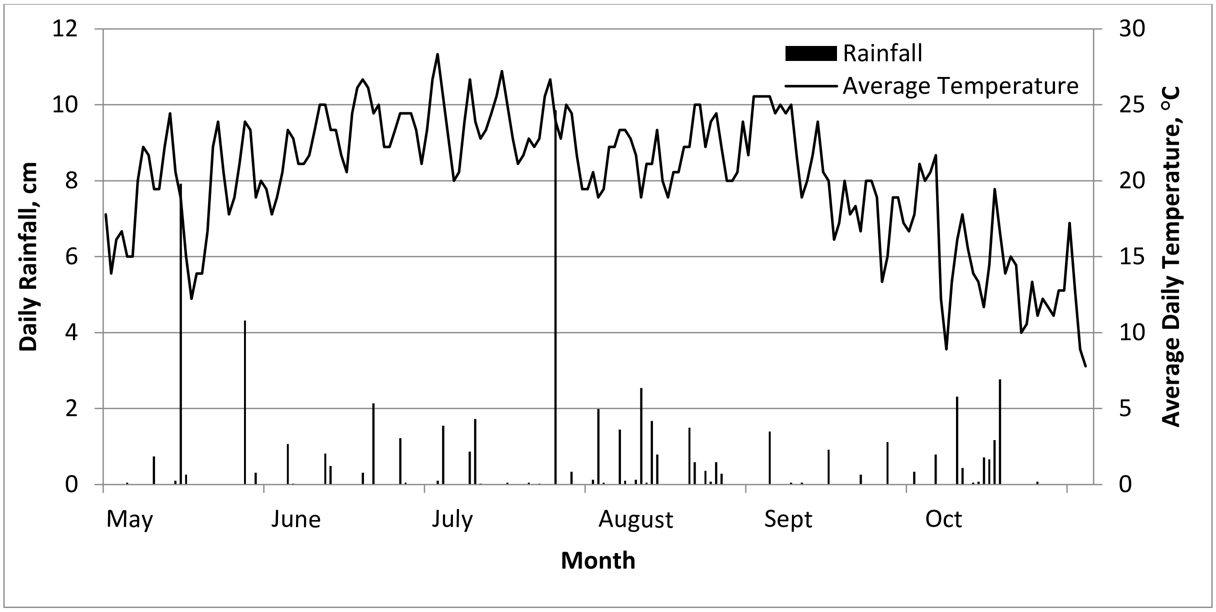
A. 2. Full-season sites 2, 3 and 4 and double-crop sites 4 and 5 daily rainfall, cm, and average temperature, °C.



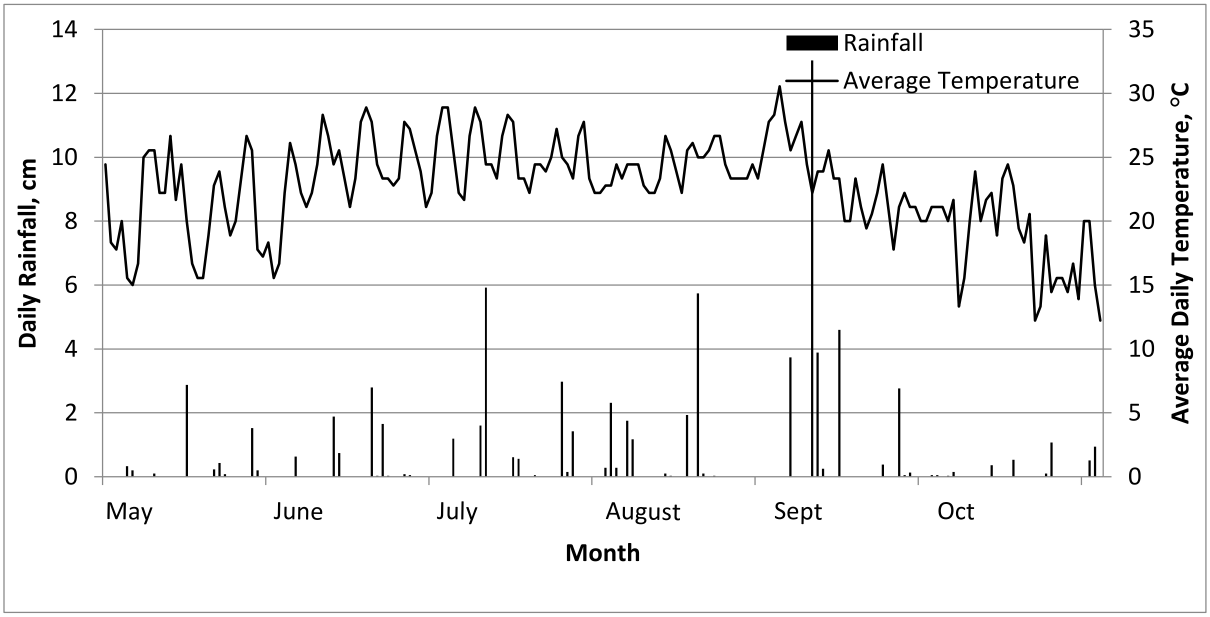
A. 3. Full-season site 5 daily rainfall, cm, and average temperature, °C.



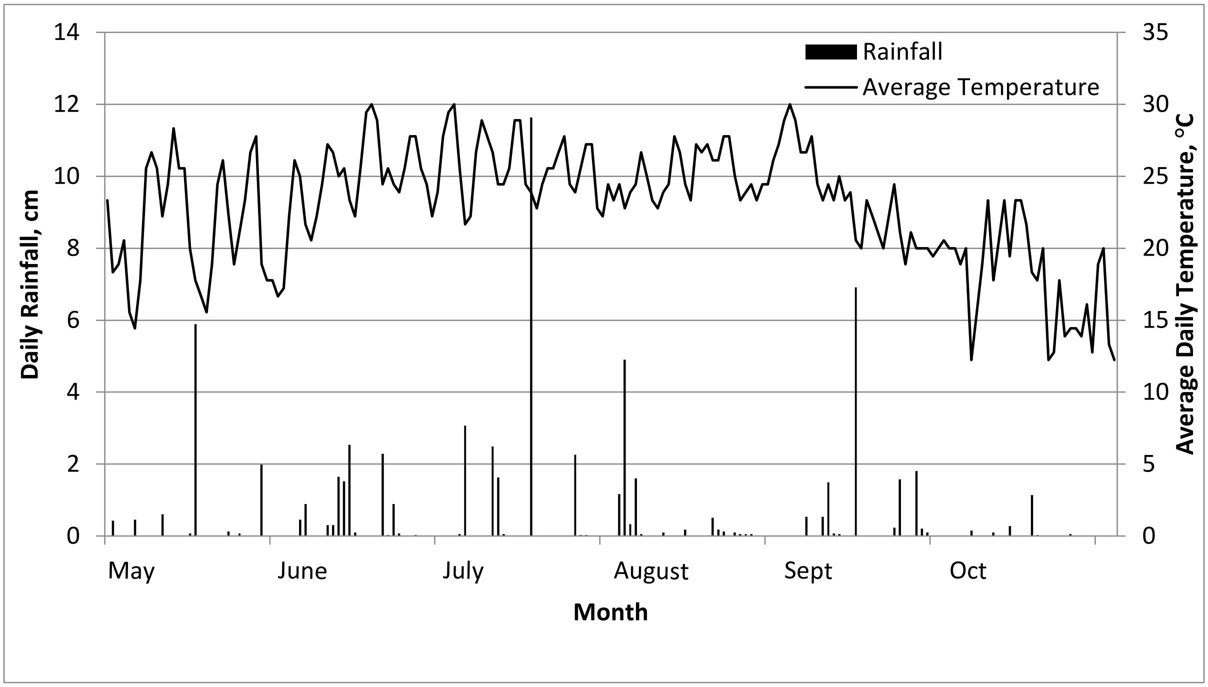
A. 4. Full-season site 6 and double-crop site 10 daily rainfall, cm, and average temperature, °C.



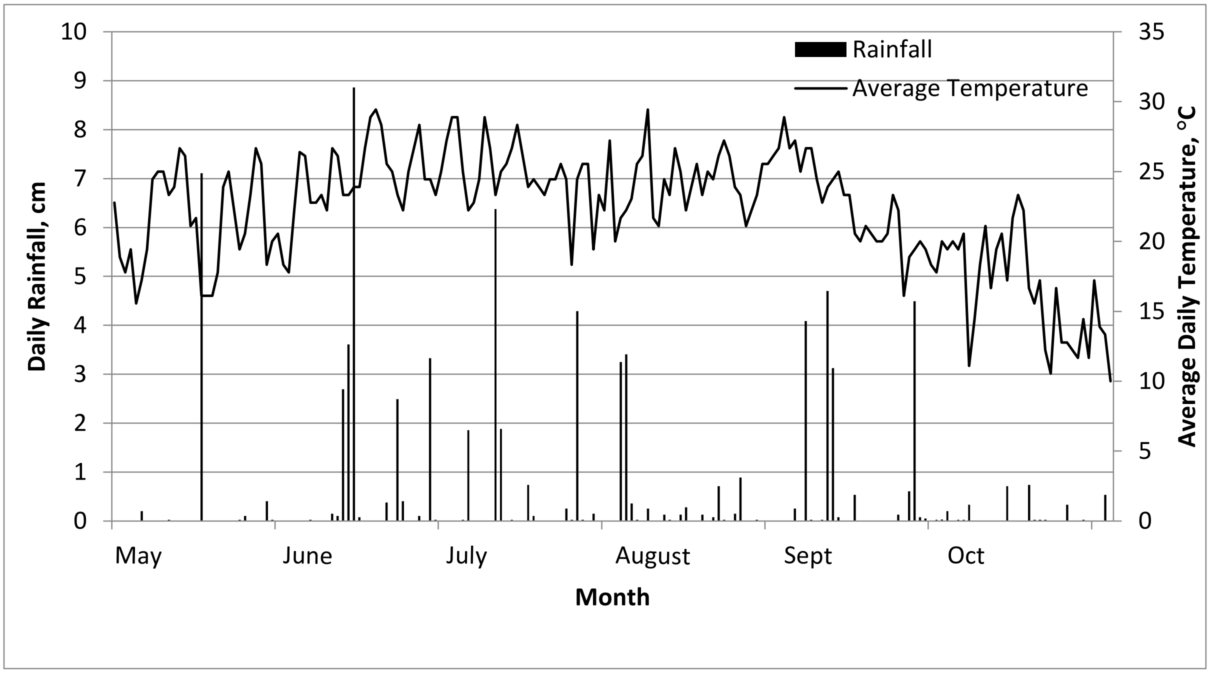
A. 5. Full-season site 7 daily rainfall, cm, and average temperature, °C.



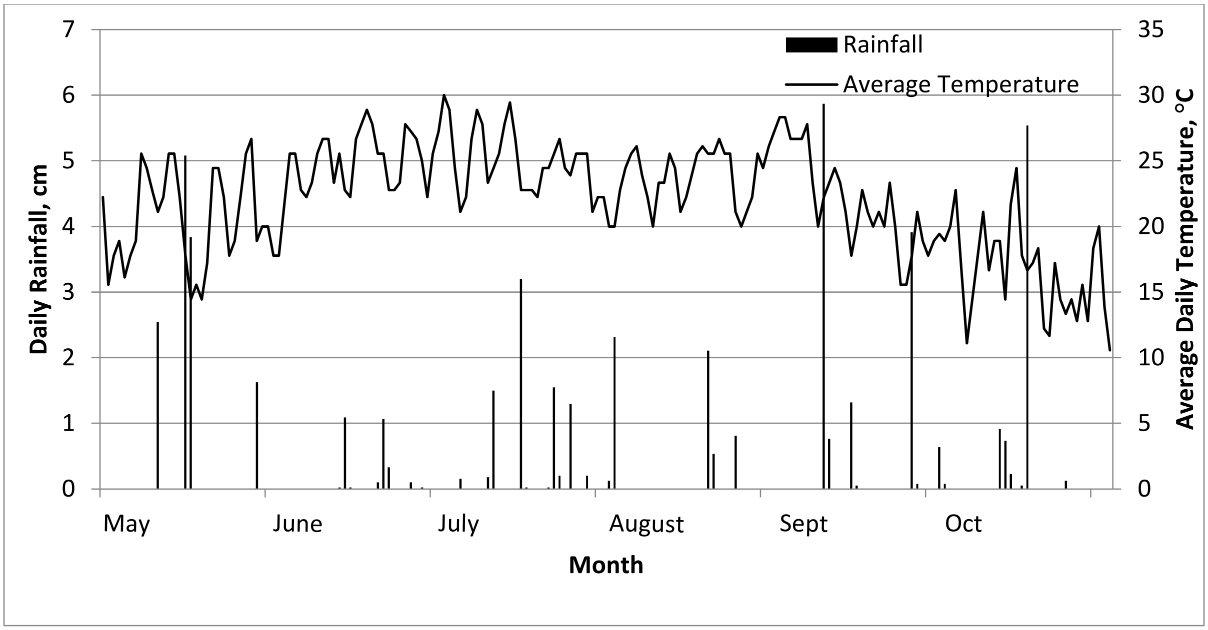
A. 6. Full-season sites 8 and 18 daily rainfall, cm, and average temperature, °C.



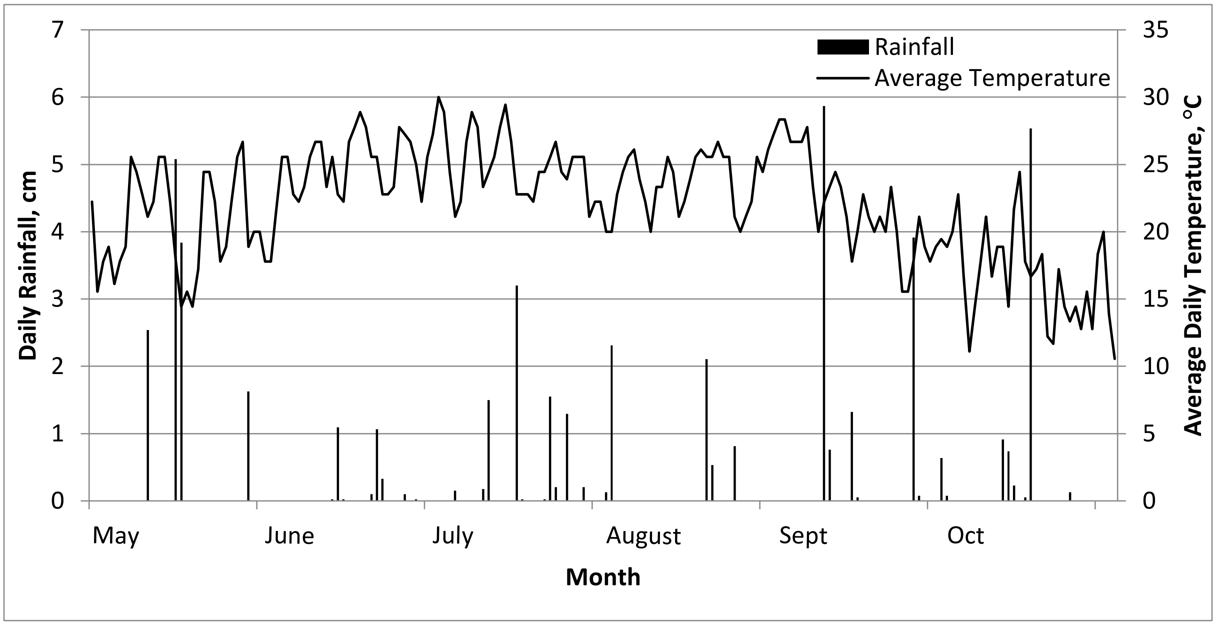
A. 7. Full-season site 9 daily rainfall, cm, and average temperature, °C.



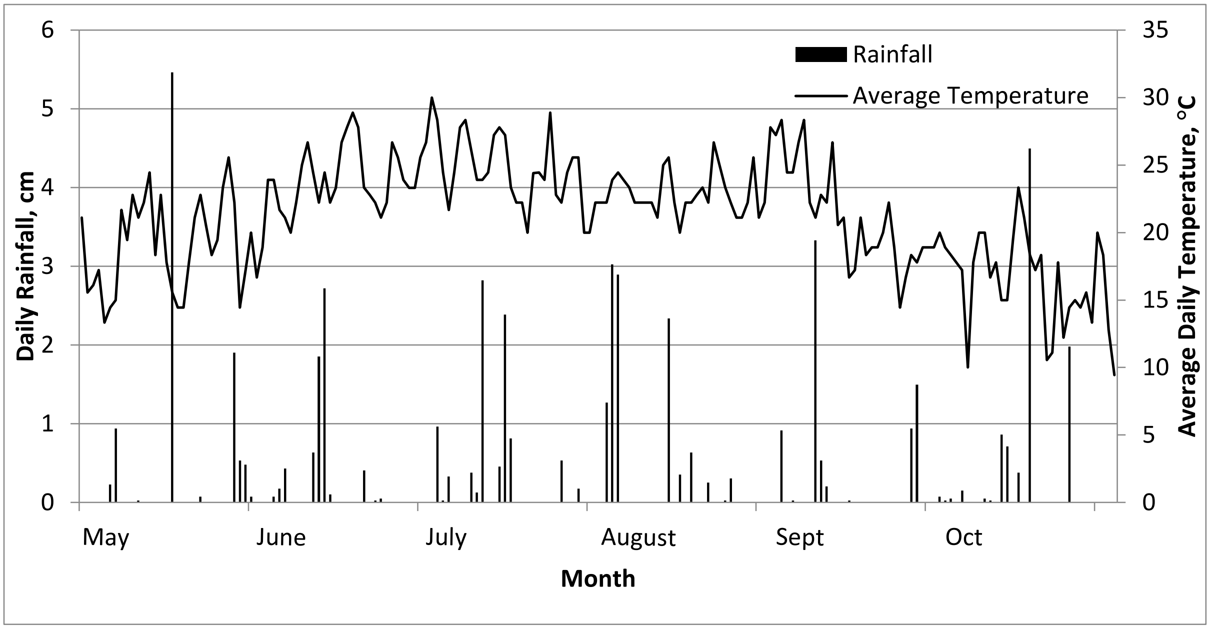
A. 8. Full-season sites 10 and 11 daily rainfall, cm, and average temperature, °C.



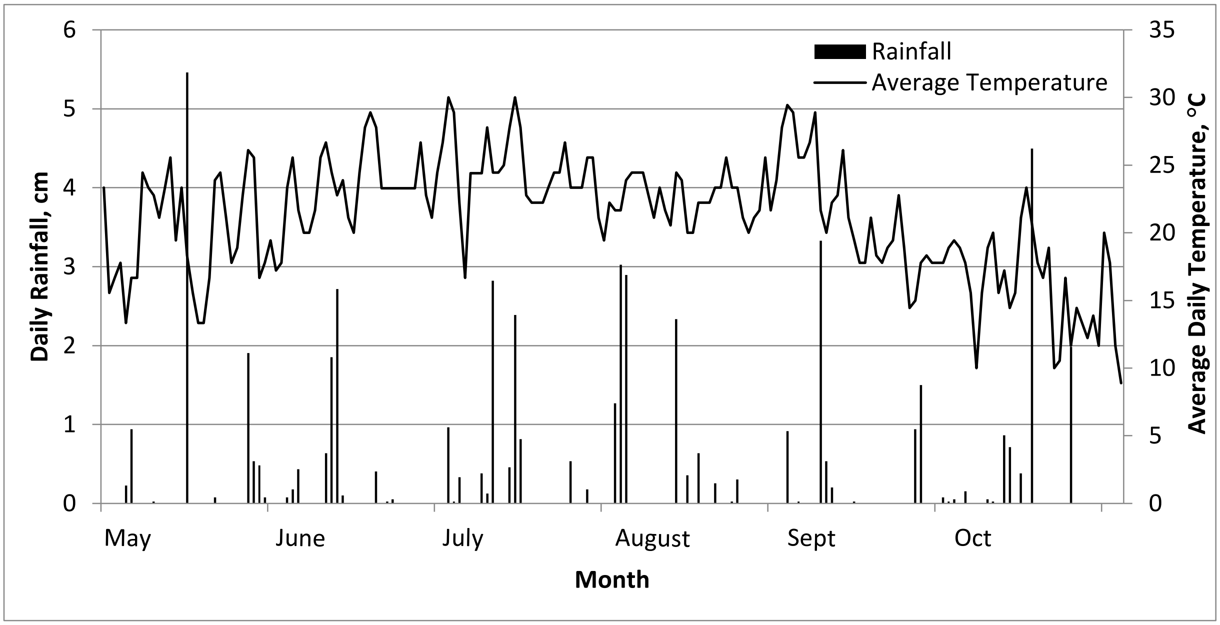
A. 9. Full-season site 12 daily rainfall, cm, and average temperature, °C.



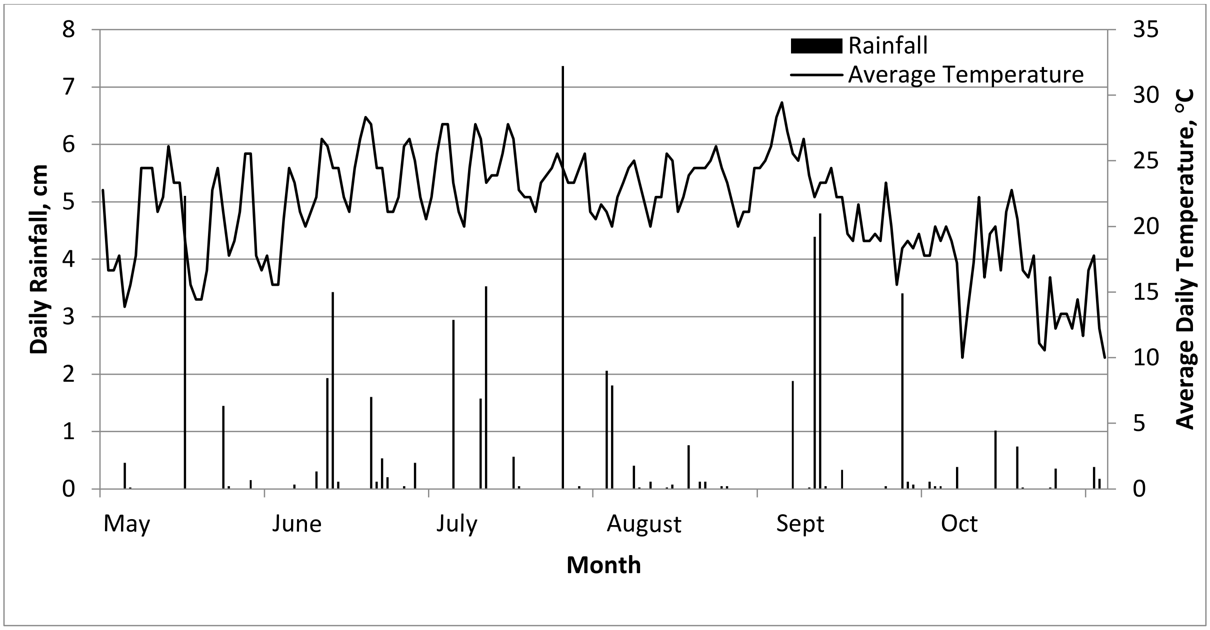
A. 10. Full-season sites 13 and 14 daily rainfall, cm, and average temperature, °C.



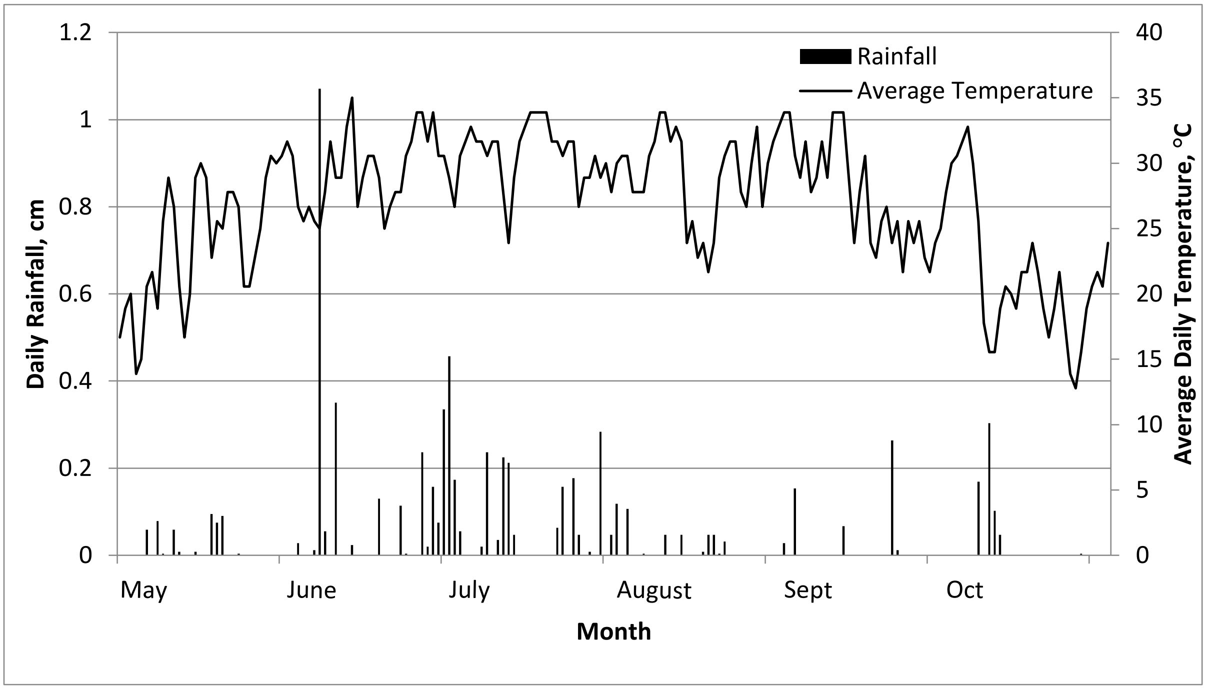
A. 11. Full-season site 15 daily rainfall, cm, and average temperature, °C.



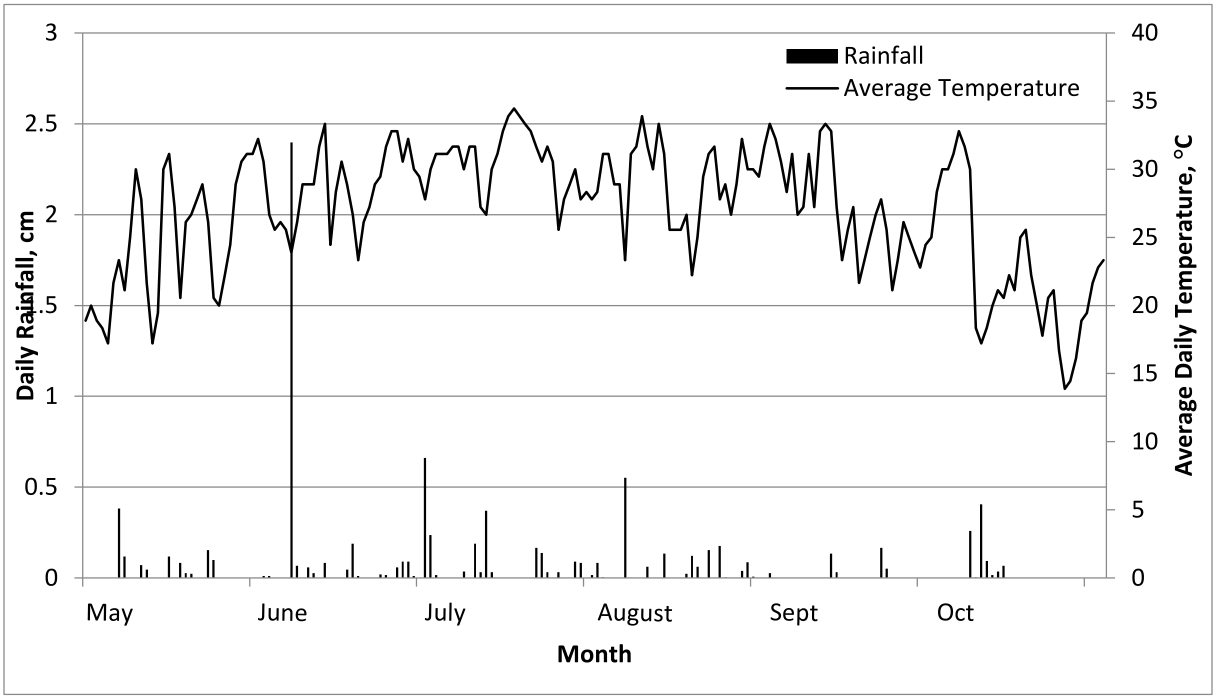
A. 12. Full-season sites 16 and 19 daily rainfall, cm, and average temperature, °C.



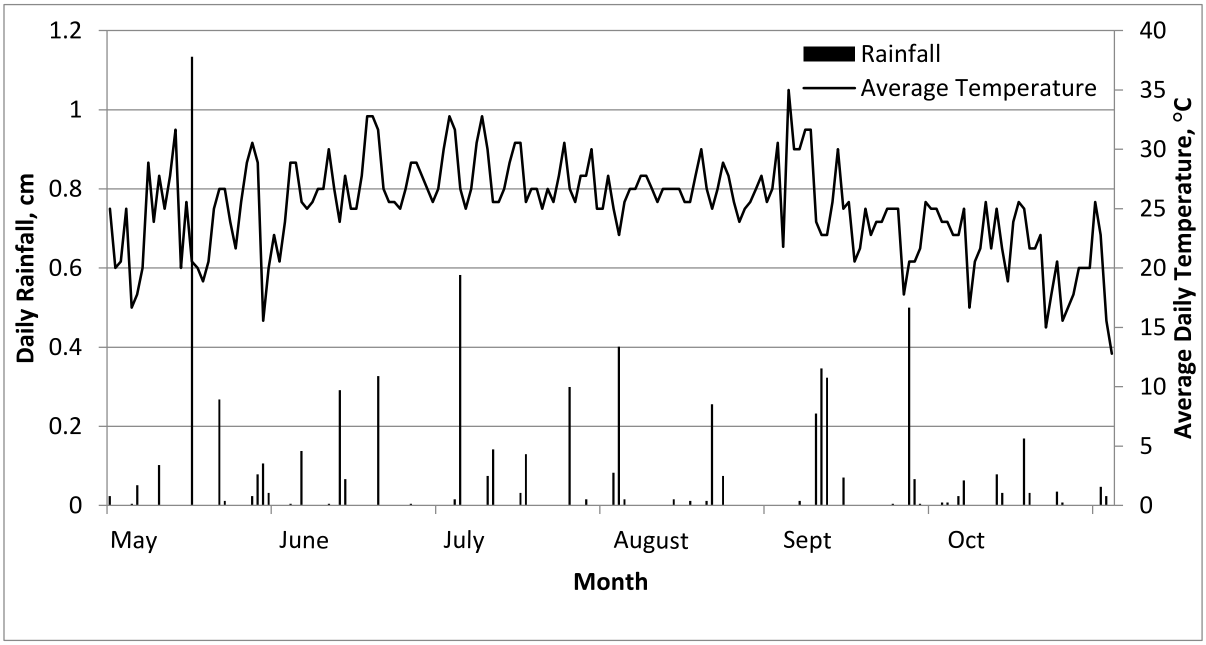
A. 13. Full-season site 17 and double-crop sites 13 and 14 daily rainfall, cm, and average temperature, °C.



A. 14. Double-crop sites 3, 6, and 7 daily rainfall, cm, and average temperature, °C.



A. 15. Double-crop sites 8 and 9 daily rainfall, cm, and average temperature, °C.



A. 16. Double-crop sites 11 and 12 daily rainfall, cm, and average temperature, °C.