Investigating Nutrient Management Innovations in Upland Cotton Production to Increase Agronomic Efficiency

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Abstract

This research was focused on increasing the efficiency of upland cotton production in the northern cotton belt through the use of new fertilizer formulations, placement, and timings. The objectives of the experiments reported in this thesis were to: 1) evaluate the effects of side-dress potassium (K), sulfur (S), and boron (B) formulation and application timing on tissue nutrient levels during the bloom period; 2) evaluate lint yield response of cotton to different formulations of nitrogen (N), K, S and B applied at side-dress; and 3) compare 5x5 banding (5 cm beside and 5cm below the seed) and deep placement of complete N-P-K-S blends to current nutrient management strategies on early season plant growth, nodes above white flower, total nodes, petiole nutrient concentrations during bloom, and lint yield. Tissue S and B concentrations were increased more often than K concentrations when the nutrients were applied with side-dress N. When evaluating P and K placement, petiole P levels were found to be significantly higher in unfertilized plots when no side-dress N was applied. Phosphorus and K placement and/or rate had no effect on lint yield when N was applied at side-dress during the study. Environmental conditions potentially influenced the response to P and K placement as 5x5 placement produced yields significantly higher during 2013 growing season at location 1, while deep placement produced significantly higher yields in 2014 at location 3. As a result, Virginia nutrient management recommendations for cotton have been updated to incorporate management strategies to maximize lint yields.

Dedication

I would like to dedicate this thesis to my family. Firstly, my wife, Mrs. Hunter Shirley Brown, has given me endless love, support, and encouragement throughout this entire process. This thesis is also dedicated to my parents. My father, Aaron Brown, has encouraged me throughout my college career, and my mother, Genia Brown, instilled in me a love for learning at an early age. Also thank you to everyone who has encouraged and prayed for me along the way as I have pursued this degree.

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1 Introduction

Upland cotton (*Gossypium hirsutum* L.) is a vital part of agriculture and the economy in the southeastern coastal plains of Virginia. Virginia cotton production is concentrated in the southeast counties of the state with a total production area of 5,398 hectares in 2014 (National Agricultural Statistic Service, 2015a). Virginia cotton producers averaged 1,388.67 kg lint ha^{-1} during 2014, the third highest average yield nationally (National Agricultural Statistic Service, 2015b). Despite a cooler climate and limited irrigated acres compared to sates throughout the United States (U.S.) cotton belt, Virginia producers routinely place in the top five highest yielding states for cotton.

In order to maintain these high yield levels producers need nutrient management strategies which optimize yield and profitability. Upland cotton is an indeterminate perennial plant cultivated as annual crop, presenting challenges not found in annual cropping systems (i.e., corn, soybeans, and winter wheat). Cotton development has been correlated with growing degree days (DD) with a base of 15.6 ^{o}C, and cotton needs 2,000 DD15.6 to reach maturity. From 2010-2014, Virginia accumulated an average of 2,546 DD15.6 per growing season (Mehl and Masters, 2015). Of that total, 910 to 950 growing degree days (40 to 80 days depending on environment) are required for bolls to fully develop (Mauney, 1986**).** Growers in the northern cotton belt must implement management strategies to maximize boll production while adequate heat units are available for development of cotton (Collins, 2006).

Cotton will abort squares and bolls (reproductive fruiting sites) throughout the growing season under conditions of nutrient and moisture stress to maintain vegetative growth (Eaton and Ergle, 1957). Soils in this region in general are coarse textured with low cation exchange capacities (CEC), resulting in many essential plant nutrients having high leaching potentials.

With Virginia's unique environment, developing fertilization practices specific to the area holds potential to limit nutrient stress, improve nutrient use efficiency, and maximize cotton lint yields for local growers.

1.1 Potassium

Potassium (K) is an essential plant nutrient that is involved in the synthesis and transportation of photosynthates to reproductive and storage organs, as well as subsequent conversions into carbohydrates, proteins, oils, and other products (Havlin et al., 2005). Cotton is more sensitive to K deficiencies than corn (*Zea mays* L.), soybean (*Glycine max* L.), or wheat (*Triticum aestivum* L.) (Cassman et al., 1989), and has been shown to be more responsive to K fertilizer than all three mentioned crops (Cope, 1981). Resistance to biotic and abiotic stresses was shown to be compromised in K deficient environments (Oosterhuis et al., 2013). Limited K during fiber development results in reduced turgor pressure during fiber elongation thus decreasing fiber length (staple) and lint yield (Abaye, 2009). Despite soil applications of K prior to planting, K deficiencies have occurred sporadically and somewhat unpredictably across the U.S. cotton belt (Oosterhuis, 2002). Increased K application rates increased cotton lint yields in multiple studies across the U.S. cotton belt (Bennett, 1965; Gormus, 2002; Khalifa et al., 2012; Pettigrew et al., 1996; Pettigrew, 2003; Read et al., 2006).

Between 72 to 74 days after emergence is considered peak bloom and when greater than 30% of the total K uptake occurs in cotton (Havely, 1976). The synchronized K demand with flowering and boll set has been exacerbated by contemporary high-yielding varieties with rapid boll sets (Schwab et al., 2000). Virginia's short growing seasons have prompted the planting of early maturing varieties with shorter bloom periods and greater per day K demand.

In 2006, widespread K deficiency in Virginia cotton occurred, attributed to extensive K uptake during high crops yields in the previous two growing seasons and early season restrictions in root growth (Roberson, 2006). Presently, Virginia growers are broadcasting their K in the form of muriate of potash prior to planting. Periods of above normal precipitation increases the potential for K leaching on the sandy soils commonly found in the coastal plain of Virginia. Georgia Cooperative Extension and North Carolina Cooperative Extension recommend broadcasting K at or before planting, along with correcting mid-season deficiencies with foliar potassium nitrate sprays (Crozier et al., 2013; Collins et al., 2013). Research in California proposes that cotton is sufficient for K if petioles during the first week of bloom range from 4.0-5.5% K, and 3.0-4.0% K during the fifth week of bloom (Mitchell and Baker, 2000).

1.2 Phosphorus

The third most limiting nutrient in cotton production is phosphorus (P), with 54 kg P_2O_5 ha^{-1} needed to produce 454 kg lint (International Plant Nutrition Institute, 2012). This nutrient is a component of cellular energy compounds such as adenosine diphosphate, adenosine triphosphate as well as deoxyribonucleic acid and ribonucleic acid (Havlin, 2005). Almost every metabolic reaction in plants involves a phosphate derivative, leading to P deficiency being associated with restricted growth and development (Havlin et al., 2005).

In cotton production, P is essential for seedling vigor, ability to cope with drought stress, proper boll maturity, and seedling development (Fixen et al., 1994). Phosphorus deficiency results in stunted cotton stands, delayed crop maturity, and reductions of lint yields, fiber strength, and micronaire (Main, 2012). Upland cotton P applications are based on soil test recommendations, utilizing various sources generally applied in conjunction with other nutrients prior to or at planting. Virginia Cooperative Extension recommendations involve maintaining P at high soil levels via starter fertilizer applications or broadcasted P prior to planting (Reiter, 2013). Tennessee recommendations range from 0-100.8 kg P_2O_5 ha^{-1} according to soil test levels (Main, 2012). In Virginia's cotton production region P deficiencies are generally associated with low pH areas (Reiter, 2013). Studies in Georgia suggest that upland cotton is sufficient in P when petioles measure more than 800 mg kg^{-1} P during the week before and first week of bloom (Mitchell and Baker, 2000). Research in Arkansas also suggest that cotton is sufficient in P if petioles are greater than 800 mg kg^{-1} P during first week of bloom (Mitchell and Baker, 2000)

1.3 Sulfur

Sulfur is critical for the synthesis of S-containing amino acids, chlorophyll, ferredoxins, and co-enzyme A (which synthesizes fatty acids, amino acids, and oxidizes intermediates of citric acid cycle) (Havlin et al., 2005). Historically, S fertilization received little attention because fertilizer and atmospheric inputs supplied soils with adequate amounts for crops (Scherer, 2001). Sulfur deficiencies have increased in multiple crops throughout the world due to reductions in use of S-containing fertilizers, greater S removal from soils by high yielding varieties, declining use of S-containing pesticides, and reduced atmospheric inputs from stricter environmental regulations (Scherer, 2001; McGrath and Zhao, 1995). The Clean Air Act enacted in 1970 reduced sulfur dioxide emissions from coal burning power plants decreasing S deposition on crop fields throughout the eastern agricultural regions. Plants utilize sulfate-S, which has similar mobility in soils as nitrate-N, resulting in high leaching potential when applied to low CEC, sandy soils. Virginia cooperative extension recommends rates of 22.4 kg S ha^{-1} except when the crop is following peanut, and states that split applications may be of benefit rather than single applications (Reiter, 2013). When cotton follows peanut in a rotation, residual S is available from gypsum applications. Georgia Cooperative Extension recommends growers to apply 11.2 kg S ha^{-1} by either pre-plant broadcast or starter fertilizer applications (Collins et al., 2013). In North Carolina recommendations are to apply 11.4-33.6 kg S ha^{-1}, but states that a two-bale crop (1,076 kg lint ha^{-1}) will utilize 22.4-33.6 kg S ha^{-1} (Crozier et al., 2013).

1.4 Boron

In cotton production, boron (B) is the most important micronutrient and is critical for flowering, pollination, and boll development (Gormus, 2005; Reiter et al., 2013). Boron deficiencies negatively affect water and nutrient transportation to new cells, flower production, and fruit development (Havlin et al., 2005). Boron occurs in soil as boric acid which is leachable, but is retained by organic matter and made plant available upon organic matter decomposition. Periods of dry weather slow the decomposition and can trigger B deficiencies (Crozier et al., 2013). Cotton will shed bolls and squares, produce deformed fiber, terminate growth at apical meristems, shortened internodes, and have decreased plant responses to N and K fertilization when B is deficient (Main, 2012).

The Virginia and North Carolina cotton production guides recommend B to be soil applied at a rate of 1.12 kg B ha^{-1} at planting, or in two foliar applications of 0.28 kg B ha^{-1} each during the growing season (Reiter, 2013; Crozier et al., 2013). Georgia Cooperative Extension recommends two foliar applications of 0.28 kg B ha^{-1} at first square and first bloom (Collins et al., 2013). Split applications are encouraged as a single application increases the potential for foliar burn. Growers commonly time these foliar applications with plant growth regulator applications, which are generally applied multiple times during the growing season.

1.5 Overall Objectives

The overall objectives of this research were to: 1) evaluate the effects of side-dress K, S, and B formulation and application timing on tissue nutrient levels during the bloom period; 2) evaluate the cotton lint yield response to different formulations of N, K, S and B applied at side-dress; and 3) compare 5x5 banding (5 cm beside and 5cm below the seed) and deep placement of complete N-P-K-S blends to current nutrient management strategies on early season plant growth, nodes above white flower, total nodes, petiole nutrient concentrations during bloom, and lint yield.

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2 Response of upland cotton to side-dress applications of potassium, sulfur, and boron

2.1 Abstract

Five upland cotton (*Gossypium hirsutum* L.*)* field studies were conducted in Virginia and North Carolina during 2012 and 2013 to evaluate a new fertilizer formulation targeting observed potassium (K) deficiencies in cotton. The objectives of the study were to 1) evaluate the effects of side-dress K, sulfur (S), and boron (B) source and application timing on tissue nutrient levels during the bloom period; and 2) evaluate the cotton lint yield response to different formulations of nitrogen (N), K, S and B applied at side-dress. A total of four fertilizer treatments in 2012 and eight treatments in 2013 were evaluated. Application rates were based on current N recommendations for cotton with side-dress totals of 67 kg N ha^{-1}, resulting in application rates of 16.8 kg K_2O ha^{-1}, 5.6 kg S ha^{-1}, and 1.5 kg B ha^{-1} applied with side-dress N in all trials. Cotton petioles were sampled each year of the study and analyzed for percent K and S. In 2013, leaf samples were collected to determine B concentration. Boron and S tissue concentrations were most responsive in increasing with applications of each respectively. Overall, there was limited change in yield or petiole K in our studies in our response to treatments, likely due to pre-plant K fertilizer applications and the medium to high K soil test levels at the experimental sites used. Lint yield was determined for all plots, and responses were limited to split application of treatments increasing lint yield at one location.

2.2 Introduction

Upland cotton (*Gossypium hirsutum* L.) is an indeterminate perennial plant managed as an annual crop in agricultural systems. Cotton will abort squares and bolls (reproductive fruiting sites) throughout the growing season under conditions of nutrient and moisture stress to maintain vegetative growth, which reduces lint yields and economic returns to producers (Eaton and

Ergle, 1957). Abiotic stress, including nutrient deficiencies, must be minimized in order to maximize lint yields in cotton production systems. A better understanding of fertilization strategies to mitigate K, S, and B deficiencies in an efficient manner in upland cotton is needed.

After N, K is the most limiting nutrient in cotton production with an uptake of 157 kg K_2O ha^{-1} needed to produce 454 kg cotton lint (International Plant Nutrition Institute, 2012). Limited K availability during fiber development reduces turgor pressure in the fibers resulting in decreased fiber staple (length) and yield (Abaye, 2009). Potassium is also involved in numerous physiological functions concerning overall plant health and resistance to biotic and abiotic stresses (Oosterhuis et al., 2013).

Potassium nutrient management has become increasingly important across the United States' cotton belt as deficiencies have become more commonplace. Potassium deficiencies have been observed during the mid-late bloom period even on soils fertilized to recommended soil test K application rates. Late-season deficiencies are assumed to be an indicator of cotton's K demand surpassing the soils ability to supply the nutrient. Greater than 30% of cotton's total K uptake occurs between 72 and 84 days after emergence, or during peak bloom (Havely, 1976). The synchronized demand has been exacerbated by contemporary high-yielding varieties with rapid boll set, resembling more determinate flowering plant species (Schwab et al., 2000).

Virginia's coastal plain coarse textured soils historically test low to medium in K due to low cation exchange capacities (CEC) (Reiter, 2013). In 2006, widespread K deficiency in Virginia cotton initiated K concerns for the area, which was attributed to depletion of soil K by high crop yields in 2004 and 2005 and restricted root growth early in the 2006 growing season (Roberson, 2006). Currently, Virginia producers broadcast their K as muriate of potash (0g N kg^{-1}- 0g P_2O_5 kg^{-1}- 60g K_2O kg^{-1}) prior to planting. This leaves K susceptible to leaching losses during periods of above normal precipitation on the sandy soils commonly found in the coastal plain of Virginia, which typically has a CEC around 2 milliequivalents 100g of soil^{-1}. In Georgia and North Carolina it is recommended to broadcast K at or before planting, and correct mid-season deficiencies with foliar potassium nitrate sprays (Crozier et al., 2013; Collins et al., 2013). Side-dressing a crop generally refers to applying plant nutrients to an emerged, growing crop. In addition to limiting K losses prior to uptake, side-dressing K has the potential to mitigate deficiencies during the bloom period by synchronizing K application with peak demand.

Potassium fertilization's impact on cotton growth and development has been well documented. Pervez et al. (2005) found potassium fertilization stimulated lengthening of sympodial branches, and increased fruit retention of the first three positions and in general lower canopy fruit during the early reproductive stage. Pettigrew (2003) compared K fertilization impacts over three years for unfertilized and K fertilized cotton and found late-season leaf area index values 23% lower and lint yields 9% less for plots receiving no K in 2 of 3 years. Bennett et al. (1965) investigated six K rates ranging from 0-560 kg ha^{-1} on a sandy loam soil, in Alabama and highest lint yields were observed from 560 kg K ha^{-1} rates. However, this treatment produced the lowest percent lint and fiber length and had the highest amount of boll rot, while 70 kg K ha^{-1} produced greatest fiber strength and micronaire (Bennett et al., 1965). Yield and lint quality of K treatments applied at first square and at first bloom showed K deficiency adversely affected reproductive growth, lint yield, and sugar translocation in upland cotton; as premature termination of reproductive growth, low boll weight, and decreased translocation of sugars out of leaves occurred (Read et al., 2006). Gormus (2002) explored side-dress K rate and timing influences on cotton production in Turkey, where soils are naturally high in K and consequently K fertilization has historically been uncommon. Rates of 0, 80, 160, and 240 kg K_2O ha^{-1} were applied, and timings of K applications were 100% during early boll development, 25% at first square + 25% at first bloom + 50% at early boll development, and 50% at first square + 50% at first bloom. The 160 kg K_2O ha^{-1} treatment yielded significantly higher seed-cotton and lint yields than all other treatments over both years. When timing was evaluated single application treatment produced significantly highest lint and seed-cotton yield (Gormus, 2002).

Evaluations of N and K rates in Mississippi resulted in plants in no-K treatments developing K-deficiency and reductions in lint yield, boll mass, lint percentage, seed mass, fiber elongation, micronaire, fiber maturity, and fiber perimeter (Pettigrew et al., 1996). Khalifa et al. (2012) also evaluated N and K rate effects and found K fertilization significantly increased yield and N uptake efficiency in two of three N rates tested.

The incidence of S deficiencies has increased in multiple crops, attributed in part to reduced atmospheric deposition (Yin et al., 2011). Decreased S deposition is the result of environmental regulation such as, the Clean Air Act of 1970; which reduced air pollution from sulfur dioxide emissions at coal burning power plants. Previous S deposition supplemented cotton with S; however, to maintain crop yields producers must now supplement the deficit resulting from cleaner air. The United States Environmental Protection Agency (EPA) classifies Virginia in the mid-atlantic region of the U.S., which averaged total sulfur deposition of 16 kg S ha^{-1} during 1989-1991, and 8 kg S ha^{-1} during 2007-2009 across 11 sites (EPA, 2010). An S deficient cotton plant exhibits chlorosis in newly formed leaf tissue and is commonly mistaken for N deficiency due to leaf chlorosis (Barton et al., 1982). Sulfur deficiency is distinguished from N deficiency as symptoms are present in the younger upper leaves of cotton, while N deficiency symptoms are observed in the lower canopy (Barton et al., 1982). Plants utilize S as sulfate which is similar to N in mobility within soils, resulting in a high leaching potential for low CEC sandy soils, commonly found in Virginia's cotton production region. To achieve high yields and minimize S leaching, S fertilizer rate recommendations must be based on crop requirement and soil S availability (Scherer, 2001).

Harris et al. (1945) showed cotton yields to positively correlate with S fertilization across locations in Florida. Yin et al. (2011) found an 8-9% lint yield increase and 4-5% micronaire increase from 22 and 34 kg S ha^{-1} broadcasted prior to planting compared to a no S control. Early season S research has found soil available S levels to dictate whether a response to broadcasted S amendments would occur **(**Barton et al., 1982b). Evaluations of seedling S requirements for eight major agricultural crops [cotton, corn (*Zea mays* L.), soybean (*Glycine max* L.), sunflower (*Helianthus annuus* L.), rice (*Oryza saliva* L.), sorghum (*Sorghum bicolor* L.), wheat (*Triticum aestivum* L.), and field bean (*Phaseolus vulgaris* L.)], by Hitsuda et al. (2005), found cotton was moderately tolerant to low S concentrations. Results indicated that uptake of S was greatest in cotton compared to the other crops, though tissue dry weights were not affected (Hitsuda et al., 2005).

Sulfur deficiency concerns increase when high N rates are used (Collins et al., 2013), which is the case when highest possible yields are sought. Crozier et al. (2007) explained the N-S connection by adding that S-deficient crops will show little or no response to N amendments until the S problem is corrected, following Liebig's law of the minimum. Connecting S applications with N could limit observed S deficiencies and maximize lint yields. The Virginia Cotton Production Guide recommends rates of 22.4 kg S ha^{-1} unless the crop is following peanuts (as residual S from gypsum applied to peanut is present), and offers that multiple application timings may be beneficial (Reiter,2013). The North Carolina Cotton Information Guide recommends 11.2-22.4 kg S ha^{-1}; however, a two-bale crop will take up 22.4-33.6 kg S ha^{-}

^{1} (Crozier et al., 2013). The University of Georgia recommends applications of 11.2 kg S ha^{-1} by means of pre-plant broadcast, starter fertilizer 28-0-0-5S, or ammonium thiosulfate applications (Collins et al., 2013).

Boron (B) is recognized as the most important micronutrient for cotton production (Gormus, 2005), as cotton requires B throughout all stages of growth (Rashidi et al., 2011). Boron is critical for flowering, pollination, and boll development (Reiter et al., 2013). Side-dressed B applications have been found to increase yields even when B deficiency symptoms were not evident in a no-B control (Anderson and Boswell, 1968). Other researchers found B additions to statistically increase cotton boll number, boll weight, seed cotton yield, and lint yields (Rashidi and Seilsepour, 2011). Rashidi and Seilsepour (2011) evaluated foliar B application of 0, 0.50 and 1.0 kg ha^{-1}. Application of 1.0 kg B ha^{-1} increased lint greater than 25% on average when compared to a no-B control, and produced lint yields significantly higher than other treatments (Rashidi and Seilsepour, 2011). Similarly, research on foliar applications of 0, 0.56, and 1.12 kg B ha^{-1} resulted in the 1.12kg B ha^{-1} rate producing lint yields significantly higher than all other treatments (Gormus, 2005). Cotton was most responsive to B additions when N levels were sufficient (Gormus, 2005). Boron deficiency was observed to decrease leaf CO_2 exchange rates, photosynthetic efficiency, suppressed plant growth, decreased dry matter accumulation and increased fruit abscission in cotton grown in a controlled environment in growth chambers (Zhao and Oosterhuis, 2003).

Despite decades of investigations on K, S, and B there has been a lack of research on coupling all of these minerals with N fertilization of cotton. Technology has been developed (by a partnership involving Weyerhaeuser N.R., Whitehurst & Associates, and Encee Chemical Sales) that allows a coated urea product to be made that supplies N, K, S and B in a single granule. Multiple nutrient products may be useful for side-dress applications in cotton systems. The objectives of this research were to: 1) evaluate the effects of K, S, and B source and side-dress application timing on tissue nutrient levels during the bloom period; and 2) evaluate the cotton lint yield response to different formulations of N, K, S and B applied at side-dress.

2.3 Materials and Methods

2.3.1 Site Characteristics

Five trials were conducted in 2012 and 2013 in Virginia and North Carolina. The trials in 2012 were conducted at two locations: the Virginia Tech Tidewater Agricultural Research and Extension Center (TAREC) in Suffolk, VA (location 1) and Southampton County, VA (location 2). In 2013, trials were conducted at three locations: TAREC (Location 3), the Eastern Shore Agricultural Research and Extension Center (ESAREC) in Painter, VA (Location 4), and the North Carolina Department of Agriculture and Consumer Services Peanut Belt Research Station located in Lewiston, NC (Location 5). A description of the soils at each location can be found in table 2.1. Soil test results from samples taken at locations before the growing season at each site is located in table 2.2.

Location 1 received pre-plant fertilization of 22 kg N ha^{-1}, 59kg P_2O_5 ha^{-1}, and 145 kg K_2O ha^{-1}. Location 2 received 45 kg N ha^{-1}, 59kg P_2O_5 ha^{-1}, and 67 kg K_2O ha^{-1} as pre-plant broadcast fertilizer and a band 5 cm to the side and 5 cm below the seed (5x5). In 2013, pre-plant phosphorus (P) and K rates were 45 kg P_2O_5 ha^{-1} and 45 kg K_2O ha^{-1} based on soil test recommendations, except location 4 which received no pre-plant P as soil tests levels were very high. All 2013 locations received 14 kg N ha^{-1} at planting in a 5x5 band as urea ammonium nitrate or ammonium polyphosphate (10-34-0) solution, depending on soil test P levels. With the exception of in-season fertilization, all other agronomic practices were conducted according to

Virginia Cooperative Extension recommendations (Reiter, 2013). Phytogen 499WRF was the cotton variety planted at all locations, except location 2 planted with Phytogen 375WRF. Cotton was planted on 91-cm wide rows, with plots being four rows in width. Location 1 and 2 plots measured 9 meters in length, while plots at locations 3, 4, and 5 were 12 meters long. Plant populations averaged 9.8 plants per row meter. Planting, key developmental stage, and harvest dates for all locations are located in table 2.3.

2.3.2 Experimental Design

In 2012, four treatments were applied to upland cotton to evaluate the response to in-season management of urea-based fertilizer formulations. Treatments evaluated the application of potassium sulfate with side-dress N application. The four treatments consisted of granular urea treated with the urease inhibitor N (n-butyl) thiophosphoric triamide (NBPT), potassium sulfate coated urea (KSCU) (36-0-9-3S), KSCU treated with NBPT, and a bulk blend of granular potassium sulfate and granular urea treated with NBPT (Bulk Blend). Treatments were applied at matchhead square at an N rate of 67 kg N ha^{-1}, 16.8 kg K ha^{-1}, and 5.6 kg S ha^{-1}. Matchead square is a growth stage in cotton, when the flower bud, excluding the bracts, is approximately the size of a larger kitchen match head. Granular treatments at all locations were hand-dispersed over crops.

Treatments during 2013 trials were expanded to include an additional split side-dress N application system as well as the addition of B to the KSCU formulation. All treatments in 2013 were treated with the urease inhibitor NBPT. There were a total of eight treatment combinations arranged in a four by two factorial design with four N sources and two N application timing strategies. Fertilizers were applied in a single application at matchead square, and as split applications with 50% of the side-dress N fertilizer applied at matchead square and 50% applied at first bloom. Nitrogen, K, S and B side-dress rates and timings can be found in Table 2.4. The N, K, and S side-dress application rates did not change during 2013 from those used in 2012.

2.3.3 Petiole Tissue Testing

To evaluate in-season nutrient status, cotton petioles were collected during the first and fourth weeks of bloom at all locations. The first week of bloom was defined as the first appearance of white flowers at each location. At both sampling intervals, 24 petioles were collected from the fourth fully unfurled main stem leaf from the top. Petioles were sampled from the first and fourth rows of each plot. Petioles were immediately detached from leaves to assure accuracy in nutrient measurements. Samples collected during 2012 (locations 1 and 2) were analyzed by A&L Eastern Laboratories (Chesterfield, VA) for percent K and S by ICP wet digestion method SW846-6010C. Petiole and leaf samples from 2013 (locations 3, 4, and 5) were analyzed at Waters Agricultural Laboratories (Camilla, GA) by ICP open vessel wet digestion with a DigiBlock 3000 (SCP Science, Baie D'Urfé, Québec). In 2013 petioles were analyzed for percent K and S, while a concentration of B analysis was conducted on leaf tissue samples.

2.3.4 Lint Yield

Lint yield was determined by harvesting cotton from the center two rows using a two-row cotton picker at locations 1, 3, 4, and 5. Two, 5-foot sections were hand harvested from the center two rows at location 2. Cotton weight was recorded from each plot and a one pound subsample was ginned, and the resulting lint weighed to determine lint percentage relative to seed cotton. Continental Eagle micro-gin with ten saw blades was utilized to gin all samples (Continental Gin Company. Prattville, Alabama).

2.3.5 Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) with PROC GLIMMIX as a randomized complete block design with four replications in SAS 9.3 (SAS Institute, 2012). Treatments for 2012 were analyzed as single treatment factors and as a four by two factorial for 2013 data. The Tukey-Kramer HSD was used to determine differences between treatments for N, K, S, and B concentration in petioles and leaves and lint yield at $\alpha = 0.1$ level of significance.

2.4 Results and Discussion

2.4.1 Petiole Potassium

Responses in petiole K concentrations during 2012 were not common with only one sampling interval having differences in petiole potassium as a result of formulation (Table 2.5). Petiole K differences were observed during the first week of bloom at location 1 with KSCU having significantly higher petiole K than the bulk blend formulation. Location 1 received 135 kg K_2O ha^{-1} pre-plant, which most likely influenced the response to side-dress K. Petiole K concentration averaged among treatments was 8.03% during the first week of bloom, and 4.23% during the 4th week of bloom at location 1. At location 3, petiole K levels among treatments averaged at 6.17% during the first week of bloom, and were 2.97% during the 4th week of bloom. All petiole K values measured were considered sufficient according to previous research in California (Mitchell and Baker, 2000), except for during the 4th week of bloom at location 3, likely a cause for limited differences among treatments. López et al. (2010) and Pettite (1994) found that K concentrations in cotton leaves decreased from the first through fifth week of bloom.

2.4.2 Petiole Sulfur

Applications of KSCU at 67 kg N ha^{-1} resulted in the application of 5.6 kg S ha^{-1}. This rate is lower than current Virginia recommendations; however cotton petiole S concentrations differed by treatment at multiple locations and sampling intervals (Tables 2.6 and 2.7). Treatment had no effect on S concentrations at location 1. Location 2 had significant different S concentrations during the first week of bloom with KSCU and the bulk blend having a greater S concentration in petioles than granular urea (Table 2.6). At location 3, at both sampling intervals petiole S concentrations were significantly influenced by treatment; interestingly urea with no S applied had the highest S concentrations by the 4th week of bloom, this can not be explained biologically (Table 2.7). When potassium sulfate was applied, either as a coating or in a bulk blend, the S concentration (mg kg^{-1}) in cotton petioles was significantly increased over urea alone for both sampling intervals at location 4 (Table 2.7). Positive response in tissue S levels coincides with Barton et al. (1982a) and Yin et al. (2011) who found leaf S levels to increase with applied S over the early to late bloom period. Sulfur concentration in petioles during the first week of bloom was increased with a single application of potassium sulfate (coated urea or bulk blend) than a split application at location 4 (data not shown). There was an interaction between application timing and coatings at location 4, however this is most likely due to the uncoated urea not increasing with the single application. The only difference in S concentration of cotton petioles observed at location 5 during the study was a significant treatment interaction during the 4th week of bloom for % S, though KSCU was less than urea. The coated materials performed similarly to the bulk blend fertilizer. However, a formulation change that increases S content of the KSCU to provide S rates between 22 kg S ha^{-1} would be optimal to fulfill recommended seasonal S demand (Reiter, 2013).

2.4.3 Leaf Boron

Only locations 3, 4, and 5 had treatments containing B. Every sampling interval across locations showed significantly higher leaf B concentrations when B was applied with the KCSU treatment except for the first week of bloom at location 5 (Table 2.8). The lack of response at location 5 is most likely due to the early season injury at that location. At the 67 kg N ha^{-1} side-dress N rate, a total of 1.5 kg B ha^{-1} was soil applied; which is more than the recommended rate for cotton and with the response to KSCU with B the formulation was effective in satisfying demand. Coating urea with B could be an economic and convenient method to apply both N and B in a one-pass system reducing fuel costs and crop damage from tractor traffic.

2.4.4 Lint Yield

Lint yields were excellent across all locations (Table 2.9 and Figure 2.2). Split application of treatments between matchead square and first bloom produced 1,839 kg lint ha^{-1}, significantly more than 1726 kg lint ha^{-1} produced by single application of treatments at matchead square at location 3. This was the only location where there was any yield response to treatments. Hand harvesting at location 2 added variability to yield results and limited the inference that can be made for this site; while early season sand-burn injury at location 5 and nutsedge pressure at location 4 delayed cotton maturity and most likely affected root growth during early season development. Increased cotton lint yield response to K (Bennett et al., 1965; Pettigrew et al., 1996; Gormus, 2002; Pettigrew, 2003; Read et al., 2006; Khalifa et al., 2012), and S (Harris et al., 1945; Yin et al., 2011) have been well documented. The lack of response in lint yield is suspected to be a combination of the current formulation not providing enough S when applied at appropriate N-based rates to fulfill season S requirement, soils testing medium to high for K (Table2.2), and abiotic factors.

2.4.5 Conclusion

Results indicate that B and S tissue concentrations were most responsive in increasing to side-dress treatments. Potassium concentrations were less responsive to side-dressed K amendments due to location sites testing medium to high for K and pre-plant K being applied at soil test recommended rates. Altering the coated urea formulations allowing more S being applied per unit of N may be optimal, as 5.6 kg S ha^{-1} was applied with the current formulation and Virginia Cooperative Extension recommends applications of 22 kg S ha^{-1} for cotton production. The higher analysis formulation would fulfill an entire seasons S demands; B season demands were met with the current formulation according to Virginia Cooperative Extension (Reiter, 2013) and tissue B levels were responsive to applications. Adding the urease inhibitor NBPT with KSCU had no effect petiole K and S, or lint yield. More research is needed on KSCU that contains a higher analysis of S to evaluate effectiveness of complete side-dress nutrient delivery in an upland cotton system. Fields with a history of K deficiency, and/or low soil test K levels may be more responsive to side-dressed K than sites tested in this study.

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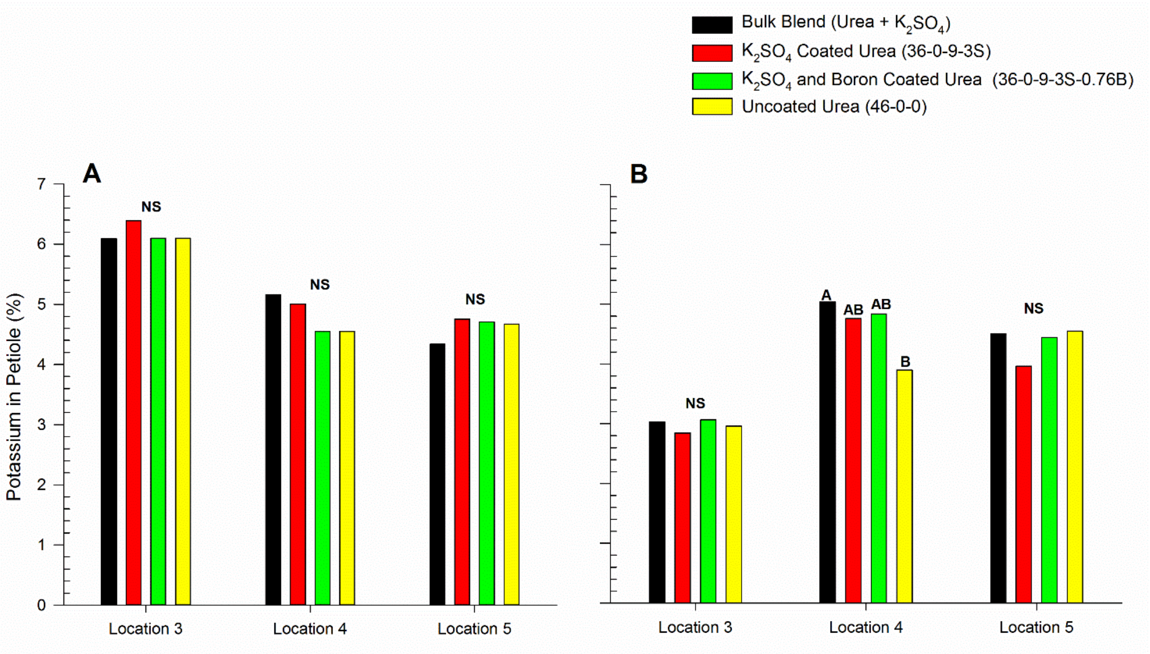

Figure 2.1: Petiole potassium levels in cotton petioles from the 4th leaf from the top during the 1st (A) and 4th (B) week of bloom for 2013 locations of a side-dress K, S, and B cotton study. Values with the same letter are not significantly different or means separation at $\alpha = 0.1$. NS over a group indicates ANOVA was not significant for treatments.

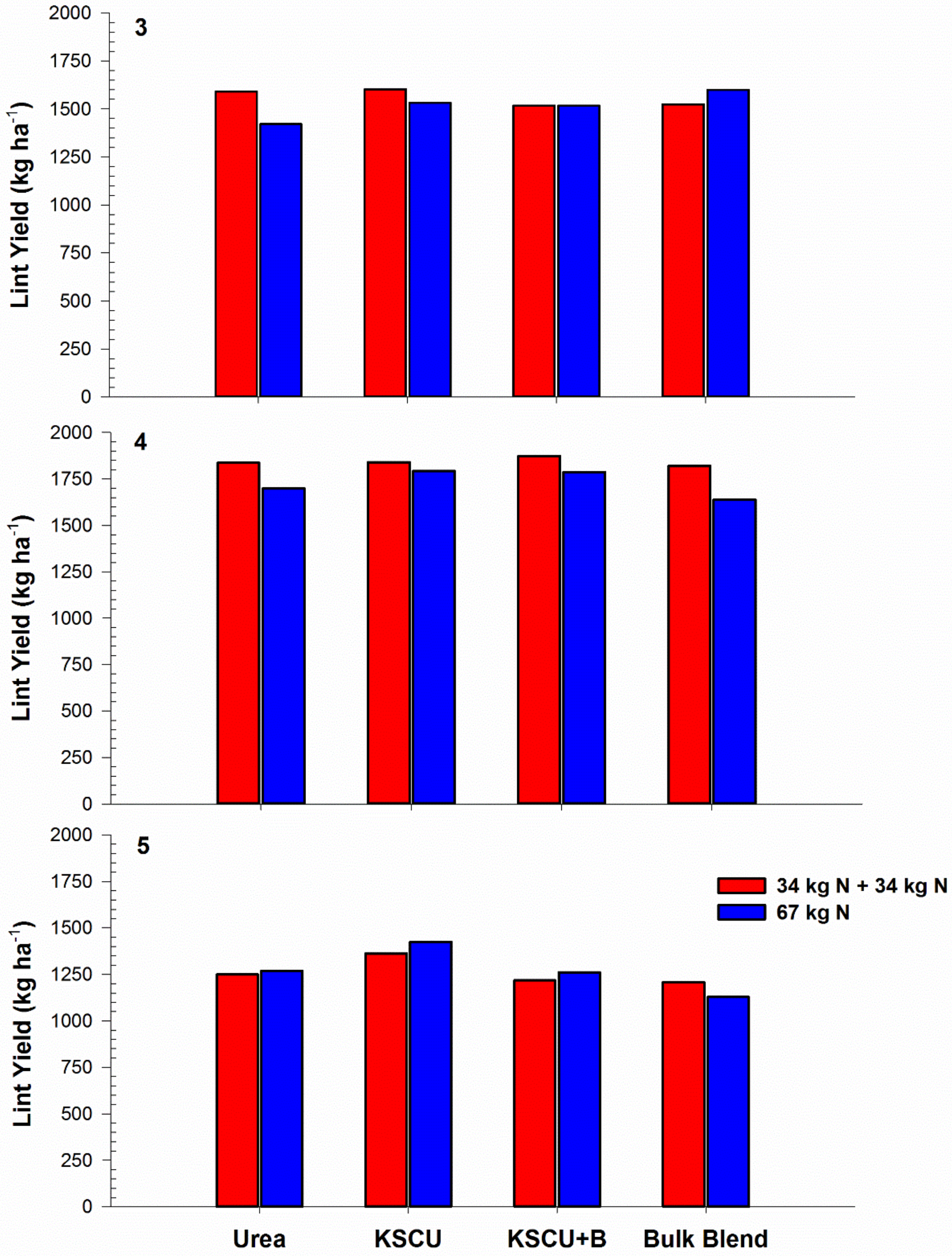

Fig. 2.2: Lint yields response to side-dress treatments for 2013 locations of a side-dress K, S, and B cotton study. Absence of letters indicates ANOVA was not significant for treatments.

Table 2.1: Soil characteristics during the 2012 and 2013 growing seasons for all locations in a side-dress K, S, and B cotton study.

Location #	Location	Series	Texture	Family
1	Suffolk, VA	Nansemond	fine sandy loam	coarse-loamy, siliceous, subactive, thermic Aquic Hapludults
2	Southampton, VA	Munden-84%	loamy sand	coarse-loamy, mixed, semiactive, thermic Aquic Hapludults
2	Southampton, VA	Altavista-16%	fine sandy loam	fine-loamy, mixed, semiactive, thermic Aquic Hapludults
3	Suffolk,VA	Eunola	loamy sand	fine-loamy, siliceous, semiactive, thermic Aquic Hapludults
4	Painter, VA	Bojac	loamy sand	coarse-loamy, mixed, semiactive, thermic Typic Hapludults
5	Lewiston, NC	Rains	sandy loam	fine-loamy, siliceous, semiactive, thermic Typic Paleaquults

Table 2.2: Mehlich I extractable K for all locations in a side-dress K, S, and B cotton study.

	1	**2ǂ**	**3**	**4**	**5**
Depth(cm.)		----------------------mg kg^{-1}----------------------			
0-15	116(H)†	-	-	74 (M)	-
0-8	-	-	99 (H-)	-	126 (H)
8-15	-	-	86 (M+)	-	59 (M)

† Indicates the soil test level based on Virginia's soil test calibration

ǂ No soil test K levels were available for location 2

Table 2.3: Planting, key developmental stages, and harvesting dates during the 2012 and 2013 growing seasons for all locations in a side-dress K,S, and B cotton study.

Location	**Planted**	**Matchhead Square**	**1st Bloom**	**Harvested**
1	5/3/12	6/21/12	7/12/12	11/5/12
2	5/4/12	6/15/12	7/5/12	10/12/12
3	5/8/13	6/24/13	7/17/13	10/21/13
4	5/21/13	7/9/13	7/24/13	12/3/13
5	5/30/13	7/18/13	7/31/13	11/19/13

Table 2.4: Treatments to evaluate side-dress nutrient source and timing for the 2013 locations of a side-dress K, S, and B cotton study.

Treatment	**Coating**	**Side-dress N Timing**	**Other Side-dress Nutrients**		
			S	K$_2$O	B
			------------- kg ha^{-1} -------------		
1	None[†]	Single[‡]	-	-	-
2	None	Split[§]	-	-	-
3	KSCU[¶]	Single	5.6	16.8	-
4	KSCU	Split	5.6	16.8	-
5	KSCU+B	Single	5.6	16.8	1.5
6	KSCU+B	Split	5.6	16.8	1.5
7	Bulk Blend (Urea + Granular K_2SO_4)	Single	5.6	16.8	-
8	Bulk Blend (Urea + Granular K_2SO_4)	Split	5.6	16.8	-

†None indicates no coating was applied, and urea fertilizer was applied
‡Single applications were made at matchead square
§Split applications were made at matchead square and 1st bloom
¶KSCU stands for potassium sulfate coated urea

Table 2.5: Petiole potassium levels in cotton petioles from the 4th leaf from the top during the 1st and 4th week of bloom for 2012 locations of a side-dress K, S, and B cotton study.

Formulation	**Potassium (%)**			
	Locations			
	1		**2**	
	1st †	4th	1st	4th
Urea	8.13 ab ‡	4.18	4.81	4.11
KSCU § w/o ¶ NBPT#	8.38 a	4.14	5.05	3.96
KSCU	8.06 ab	4.32	4.92	3.83
Bulk Blend ††	7.54 b	4.28	5.28	3.81
Pr > F	**0.0702**	**NS‡‡**	**NS**	**NS**

†1st and 4th indicate the week of bloom the petioles were sampled.

‡Values with the same letter are not significantly different for means separation at α = 0.1 within columns. Absence of letters indicates ANOVA was not significant.

§KSCU=potassium sulfate coated urea

¶w/o=without

NBPT=N-(n-butyl) thiosphoric triamide

††Bulk Blend=Blended granular urea and potassium sulfate

‡‡ANOVA was not significant.

Table 2.6: Petiole sulfur levels in cotton petioles from the 4th leaf from the top during the 1st and 4th week of bloom for 2012 locations of a side-dress K, S, and B cotton study.

Formulation	**Sulfur (%)**			
	Locations			
	1		**2**	
	1st †	4th	1st	4th
Urea	0.15	0.13	0.14 b ‡	0.12
KSCU § w/o ¶ NBPT#	0.15	0.13	0.17 a	0.13
KSCU	0.14	0.13	0.16 ab	0.13
Bulk Blend††	0.14	0.13	0.17 a	0.13
Pr > F	**NS‡‡**	**NS**	**0.0226**	**NS**

†1st and 4th indicate the week of bloom the petioles were sampled.

‡Values with the same letter are not significantly different for means separation at α = 0.1 within columns. Absence of letters indicates ANOVA was not significant.

§KSCU=potassium sulfate coated urea

¶w/o=without

NBPT=N-(n-butyl) thiosphoric triamide

††Bulk Blend=Blended granular urea and potassium sulfate

‡‡ANOVA was not significant.

Table 2.7: Petiole sulfur levels in cotton petioles from the 4th leaf from the top during the 1st and 4th week of bloom for 2013 locations of a side-dress K, S, and B cotton study.

Formulation	**Sulfur (%)**					
	Locations					
	3		**4**		**5**	
	1st †	4th	1st	4th	1st	4th
Urea	0.10 b ‡	0.06 a	0.05 b	0.08 b	0.20	0.14
KSCU §	0.13 ab	0.05 b	0.09 a	0.14 a	0.17	0.12
KSCU + B	0.14 a	0.05 ab	0.08 a	0.13 a	0.18	0.14
Bulk Blend ¶	0.13 ab	0.04 b	0.09 a	0.16 a	0.17	0.14
Pr > F	**0.0677**	**0.0148**	**0.0002**	**0.0014**	**NS**	**NS**

†1st and 4th indicate the week of bloom the petioles were sampled.

‡Values with the same letter are not significantly different for means separation at α = 0.1 within columns. Absence of letters indicates ANOVA was not significant.

§KSCU=potassium sulfate coated urea

¶ Bulk Blend=Blended granular urea and potassium sulfate

ANOVA was not significant.

Table 2.8: Leaf boron concentrations in cotton leaves from the 4th leaf from the top during the 1st and 4th week of bloom for 2013 locations of a side-dress K,S, and B cotton study.

Formulation	**Leaf Boron Concentrations**					
	Locations					
	3		**4**		**5**	
	1st †	4th	1st	4th	1st	4th
	---------------------------------- mg kg^{-1}----------------------------------					
Urea	34.8 b ‡	36.9 b	26.0 b	31.0 c	38.2	59.2 b
KSCU §	36.4 b	40.9 b	30.0 b	39.1 b	34.3	60.1 b
KSCU + B	44.6 a	60.7 a	37.2 a	48.3 a	37.5	69.2 a
Bulk Blend ¶	32.8 b	36.5 b	28.6 b	34.5 bc	37.1	60.3 b
Pr > F	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**NS#**	**<0.0001**

†1st and 4th indicate the week of bloom the petioles were sampled.

‡Values with the same letter are not significantly different for means separation at α = 0.1 within columns. Absence of letters indicates ANOVA was not significant.

§KSCU=potassium sulfate coated urea

¶ Bulk Blend=Blended granular urea and potassium sulfate

ANOVA was not significant.

Table 2.9: Lint yields (kg ha^{-1}) at 2012 locations of a side-dress K,S, and B cotton study.

Formulation	**Location**	
	1	**2**
Urea	1360 [†]	1681
KSCU [‡] w/o [§] NBPT[¶]	1485	1577
KSCU	1472	1630
Bulk Blend [#]	1593	1555
Pr > F	**NS**[††]	**NS**

†Absence of letters indicates ANOVA was not significant.
‡KSCU=potassium sulfate coated urea
§w/o=without
¶ NBPT=N-(n-butyl) thiosphoric triamide
#Bulk Blend=Blended granular urea and potassium sulfate
††ANOVA was not significant.

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3 Phosphorus and Potassium Fertilizer Rate and Placement in Upland Cotton

3.1 Abstract

A total of four upland cotton (*Gossypium hirsutum* L.*)* field studies were conducted in Virginia and North Carolina to evaluate pre-plant phosphorus (P) and potassium (K) management strategies over the 2013 and 2014 growing seasons. Research objectives were to: 1) compare 5x5 banding (5 cm below the seed and 5 cm beside the seed) and deep placement of complete N-P-K-S blends to current nutrient management practices on early season plant growth, nodes above white flower, total nodes, petiole nutrient concentrations during bloom, and lint yield; and 2) determine impacts of P and K rate placed in a 5x5 band at planting and deep placement with strip-tillage on early season plant growth, nodes above white flower, total nodes, petiole nutrient concentrations during bloom, and lint yield. The fluid fertilizer application methods were 5 cm beside and 5 cm below the seed at planting (5x5 banding), and deep placement of P and K blends during strip tillage in bands at depths of 15, 23, and 30 cm. Early season growth, petiole nutrient concentrations during the bloom period, total nodes, nodes above white flower, and lint yield were measured. Nine treatments were replicated four times in a randomized complete block design at each site; which included an unfertilized control, granular broadcast fertilizer control, liquid P starter control (ammonium polyphosphate solutions), and three rates of P and K applied in each a 5x5 band and deep placement. Results showed that no applied nitrogen (N) elevated P concentrations in cotton petioles throughout the bloom period. The unfertilized control with no N or pre-plant P had the highest P concentrations over all nutrient management systems than systems where N and P were applied during 23 out of 27 sampling intervals at locations 1, 2, and 3. The unfertilized checks also had the shortest plant

heights, being significantly shorter than all fertilized treatments during 12 out of 18 sampling intervals at locations 1, 3, and 4. At location 1, 5x5 banding increased lint yields compared to deep placement, with 2,244 kg lint ha^{-1} and 2,082 kg lint ha^{-1}, respectively during 2013. At location 3 deep placement increased lint yields compared to 5x5 banding, with 2,212 kg lint ha^{-1} and 2,025 kg lint ha^{-1}, respectively during 2014. The 5x5 banded and deep placement of nutrients produced similar yields to current nutrient management systems during the course of the trial.

3.2 Introduction

In the upper southeast coastal plain region of upland cotton (*Gossypium hirsutum* L.*)* production areas, growers would benefit from practices that stimulate early season growth. The Virginia Coastal Plains has a shortened growing season compared to other areas of the cotton belt (~200 days). The benefits of stimulating early season growth include: limiting the period of susceptibility to thrips damage, increasing competiveness with early season weeds, hastening emergence, more uniform stands, and decreasing susceptibility to fall frost injury during boll opening. This study focused on banded placement of P and K as well as application rate in the upper southeast coastal plain.

The predominant tillage system used in Virginia cotton production is strip tillage, a form of conservation tillage. Strip tillage disturbs the soil to a depth of 25 - 40 centimeters (cm) directly below the row and 15 - 30 cm wide strip on the soil surface, while maintaining a soil cover in the row middles. Sub-surface tillage promotes cotton root development, while the cultivated strip promotes soil warming, rapid germination, and uniform stand. Strip tillage can be conducted prior to planting or in conjunction with planting. Placing P and K fertilizer at depths of 15-20 cm in the tilled band of strip till systems has been investigated in corn and soybean production systems (Borges and Mallarino, 2000; Farmaha et al., 2011; and Fernández and White, 2012).

Broadcasting fertilizer sources maximizes the contact with the soil colloids, increasing soil fixation of P and K. Banding fertilizer limits soil fixation; which increases plant availability and fertilizer efficiency (Anonymous, 1999). In strip tillage systems banding fertilizers may prove to be both economically and environmentally relevant as fertilizer rates increase so does cost of production and potential for harmful off-target effects from excess fertilizer moving off site.

Deep placement of nutrients at multiple depths offers the potential to keep P and K plant available longer during the growing season as roots grow into nutrient rich zones. In contrast, 5x5 banding is placement of fertilizer 5 cm beside the seed and 5 cm below the seed. Upland cotton has shown variable response to starter fertilizers containing P and K; however, no studies have been conducted looking at deep placement and 5x5 banding in Virginia (Adeli and Varco, 2002; Bednarz et al., 2000; Crozier et al., 2013; Fixen et al., 1994; Funderburg, 1988; Guthrie et al., 1991; Howard and Hutchinson, 1997; Toler et al., 2004; and Touchton et al., 1986).

Soils in the cotton production region of Virginia generally test high to very high for P and deficiencies are often associated with low pH areas; while it is recommended to maintain soil levels in the high range due to P’s role in seedling development (Reiter, 2013). Drew (1975) conducted experiments on barley (*Hordeum vulgare subsp. vulgare*) and found that banded phosphate increased root proliferation in the banded region with minimal affects to shoot development. Increased root proliferation enables increased uptake of nutrients and water, and consequently promotes overall health of plants.

In-season fertilizer applications to correct P deficiency seldom proves effective for cotton (Crozier et al., 2013); affirming the importance of P placement at or prior to planting. Phosphorus is immobile in soils, prompting its application as a starter fertilizer (Collins et al., 2013). When soil test P levels are low and rates are modest, banding P fertilizer has shown the greatest benefits over broadcast applications, with differences between methods declining as application rate increases (Anonymous, 1999).

Banding may be an effective method to satisfy upland cotton's K demand. Potassium is essential for cotton production due to its role in fiber development, staple (length), and yield (Abaye, 2009). Potassium is involved in numerous physiological functions concerning overall plant health and resistance to biotic and abiotic stresses (Oosterhuis et al., 2013). Currently, Virginia producers broadcast their K as muriate of potash (0-0-60) prior to planting. In Georgia and North Carolina it is recommended to broadcast K at or before planting, and correct mid-season deficiencies with foliar potassium nitrate sprays (Crozier et al., 2013; Collins et al., 2013). Potassium nitrate sprays are limited in the rate of K that can be applied at one time due to crop injury concerns, making early season K nutrient management important in cotton production systems. Cotton responsiveness to K has been well documented with increases in lint yields with increasing K application rates (Bennett et al., 1965; Pettigrew et al., 1996; Gormus, 2002; Pettigrew, 2003; Read et al., 2006; Khalifa et al., 2012).

Virginia's coastal plain sandy textured soils routinely test low to medium for K due to low cation exchange capacity (CEC) (Reiter, 2013). Low CEC soils have increased leaching potentials for positively charged ions, like K. Applying starter K in liquid sources at different depths may allow roots to grow into nutrient zones rich in K as the season progresses; and consequently minimize K deficiencies, maximize fertilizer use efficiency, and increase lint yields. Adeli and Varco (2002) compared 5x5 banding and broadcast incorporation of K over three years in Mississippi, with a combination of the two methods increasing lint yield most efficiently, while producing greatest total K uptake and leaf K concentrations. Banded K alone was directly related to increased lint yield in 1 of three years, when below average rainfall was observed (Adeli and Varco, 2002).

Bednarz et al. (2000) compared 5x5 banded fertilizers containing N, P, K, and various micronutrients, with plant responses to source dependent on soil type. At one site when an extended period of cool weather occurred after planting, starter fertilizers positively affected yield, as soil P mineralization was thought to be reduced (Bednarz et al., 2000). In comparisons of 5x5 banded and 10-cm surface band applications of urea ammonium nitrate and ammonium polyphosphate found that environmental conditions affect crop responses to the fertilizer source (Toler et al., 2004). They also reported that starter fertilizer did not affect cotton yield when early season moisture was adequate, but when conditions were dry ammonium polyphosphate produced optimal yields. Guthrie et al. (1991) evaluated banded 5x5 and broadcast starter N and P fertilizer over four site years in North Carolina. Results showed 5x5 banded starters to promote initial flowering 3-4 days earlier and increased lint yields by 9% compared to broadcast applications (Guthrie et al., 1991). Other replicated trials in North Carolina showed maximum yield benefits from starter P fertilizers when phosphorus soil levels were low, though soils testing high in phosphorus had an average increase of 67.3 kg of lint ha^{-1} more than those not fertilized (Crozier et al., 2013). Crozier et al. (2013) reported yield responses occurred more consistently when P was applied in a 5x5 band versus surface banded applications.

Touchton et al. (1986) evaluated conventional till, no-till, and no-till with in-row sub-soiling, and nutrient placements of: deep placement at 15-20 cm below the seed and 5x5 placement of 15-0-0, 15-15-0, and 15-15-15 in Alabama. Sources applied were urea ammonium nitrate, ammonium polyphosphate, and muriate of potash. They concluded that starter fertilizers in general increased early season plant heights consistently on sandy loam soils though seed cotton yields were not related to early season growth measurements. For silt loam soils 5x5 placed 15-15-0 and 15-15-15 produced highest yields when conventional or no-till was used; and on a sandy loam 5x5 placement of 15-15-15 produced highest yields regardless of tillage (Touchton et al., 1986). When comparing various starter placements of 11-37-0 fertilizer in no-till and conventional-tillage systems, Howard and Hutchinson (1997) found starters to increase cotton yields over broadcast fertilization in 3 out of 12 sites in Tennessee and Louisiana. In Mississippi, 13 out of 18 replicated trails showed average lint yield increases of 104 kg lint ha^{-1} to banded 10-34-0 starter (Funderburg, 1988).

Our study evaluated responses to treatments placing fluid fertilizers at multiple depths in conjunction with strip tillage and planting, and current management practices. Initiating fertilizer applications that coincide with primary tillage events and planting decreases the potential number of trips across the field thus decreasing fuel costs. The objectives of this research were to: 1) compare 5x5 banding (5 cm below the seed and 5 cm beside the seed) and deep placement of complete N-P-K-S blends to current nutrient management practices on early season plant growth, nodes above white flower, total nodes, petiole nutrient concentrations during bloom, and lint yield; and 2) determine impacts of P and K rate placed in a 5x5 band at planting and deep placement with strip-tillage on early season plant growth, nodes above white flower, total nodes, petiole nutrient concentrations during bloom, and lint yield.

3.3 Materials and Methods

3.3.1 Site Characteristics

Four trials were conducted at Virginia Tech's Tidewater Agricultural Research and Extension Center (locations 1 and 3) in Suffolk, VA and the North Carolina Department of Agriculture and Consumer Services Research Station in Lewiston, NC (locations 2 and 4). Trials were conducted during the 2013 and 2014 growing seasons, with sites being in different fields each year. A description of the soils at each location can be found in table 3.1. Cotton was planted on 91-cm wide rows, with plots being four rows in width, and measuring 12 meters in length. Phytogen 499 WRF was planted at all locations. Soil samples were taken to a total depth of 31 cm and split into depths of 0-8, 8-15, 15-23, and 23-31 centimeters. Mehlich 1 soil test values for all locations can be found in Table 3.2. The 100% rate was based on Mehlich 1 soil test levels. With the exception of P and K placement and rate treatments, all other agronomic practices were conducted according to Virginia Cooperative Extension recommendations including side-dressed N and B.

3.3.2 Experimental Designs

Nine treatments were applied at all locations to evaluate response to early season P and K fertilizer placement and rate (Table 3.3). Treatment 1 served as a check and received no fertilizer anytime throughout the growing season at locations 1 and 3, and received only side-dress N at locations 2 and 4. Treatments 2 and 3 represent agronomic controls with treatment 2 having all P and K fertilizer broadcasted in granular form to soil test recommendations before planting, and treatment 3 having 112 kg ha^{-1} of 10-34-0 applied in a 5x5 band at planting with K broadcasted. Treatments 4-9 evaluated rate and placement of P and K at 50, 100, and 150% the soil test recommended application rates, with the 100% rate equaling 45 kg P_2O_5 and 45 kg K_2O per hectare for each location during the study. Treatments 4-6 evaluated P and K placed in a 5x5 band at planting and treatments 7-9 evaluated deep placement of P and K during strip tillage.

Strip-tillage, planting, and harvesting dates for all locations are in table 3.4. The strip tillage implement was equipped with three stainless steel tubes on the rear of the ripper-shanks to deeply place liquid fertilizer (Fig. 3.1). The tubes were modified to dispense fertilizer 15, 23, and 30 cm below the soil surface, with holes drilled 90^o to the direction of travel, enabling fertilizer to disperse outwards and contact the soil at various depths during strip tillage. The 5x5 band applications were made at planting using a two-row Monosem planter outfitted with a coulter and fertilizer knife to deliver liquid fertilizer 5 cm beside seed furrow and 5 cm below the seed. Granular fertilizer sources were evenly broadcast by hand to the soil surface for treatments 2 and 3. Liquid fertilizer formulations were mixed in pressurized canisters, and delivered through a carbon dioxide pressurized system for the 5x5 band at planting and deep placement during strip-tillage.

Ammonium polyphosphate (10-34-0) was the fluid P source and potassium thiosulfate (0-0-25-17S) was the fluid K source. Diammonium phosphate (18-46-0) served as the granular P source and potassium chloride (0-0-60) was the granular K source. Nitrogen and S were balanced among treatments using urea-ammonium nitrate solutions (30-0-0) (UAN30) and ammonium thiosulfate (12-0-0-26S). Each treatment received 39 kg N ha^{-1} and 46 kg S ha^{-1} to balance the N and S, except the unfertilized control (treatment 1). The extra N and S was applied during the strip-tillage application for treatments 2 and 3.

3.3.3 Early Season Plant Growth

Plant height measurements began with the appearance of the second true leaf and continued weekly until the first week of bloom. Five plants were selected at random in each plot and measured from the ground to the intersection of the uppermost petiole and leaf blade.

3.3.4 NAWF and Number of Nodes

Nodes above white flower (NAWF) were counted weekly on five randomly selected plants in each plot from the first week of bloom until NAWF were less than four. Nodes above white flower is an indication of maturity and illustrates when plants are ceasing vegetative growth. The number of total nodes were counted over two weeks beginning at first square and continuing until the first week of bloom for locations 1 and 2, while at locations 3 and 4 total number of nodes were counted at the first week of bloom.

3.3.5 Petiole Nutrient Concentrations During Bloom

To evaluate in-season nutrient status, cotton petioles were sampled from the first through the ninth week of bloom at all locations. Tissue samples were collected from the fourth fully unfurled main stem leaf from the apical meristem. Samples were taken from the first and fourth rows of each plot as to not impact lint yield measured from center two rows. Petioles were immediately detached from leaves to assure accuracy in nutrient measurements. Petiole samples were dried to a constant weight at 60 ^{o}C, ground to pass a 1 mm sieve, and sent to Waters Agricultural Laboratories (Camilla, GA), for analysis of nitrate-N, phosphorus, potassium, and sulfur by ICP open vessel wet digestion with a DigiBlock 3000 (SCP Science, Baie D'Urfé, Québec).

3.3.6 Lint Yield

Lint yield was determined by harvesting the cotton from the center two rows using a two-row commercial cotton picker. Cotton weight was recorded from each plot and a one pound subsample was ginned, and the resulting lint weighed to determine lint percentage relative to seed cotton. A Continental Eagle micro-gin with ten saw blades was utilized to gin all samples.

3.3.7 Statistical Analysis

The statistical analysis of the treatments included an analysis of variance (ANOVA) conducted using SAS 9.3 (SAS Institute, 2011). The P and K rates were analyzed using a factorial analysis in Proc GLIMMIX in SAS 9.3 (SAS Institute). Individual P and K management systems were compared using a single factor treatment design in Proc Mixed using SAS 9.3. All treatment analyses were compared at $\alpha = 0.1$ level of significance using the Tukey-Kramer mean separation procedure.

3.4 Results and Discussion

3.4.1 Nutrient Management System

3.4.1.1 In-season Plant Growth Measurements

After the first sampling interval plants heights were significantly responsive to nutrient management system at location 1 (Table 3.5). At all but one sampling interval, the 5x5 band of N-P-K-S produced the tallest plant heights compared to all other systems, producing significantly taller plants than deep placement (100%), broadcast control, and unfertilized check on the June 26th and July 3rd sampling intervals at location 1. No plant height differences were observed at location 2 during the study (Table 3.6). The lack of response in plant height is due to early season injury caused by sand-burn, which delayed and adversely affected development of the cotton at that location. Differences in plant heights from nutrient management systems were observed over all sampling intervals at locations 3 and 4, though deep placement of N-P-K-S blends produced the tallest plant heights at two of six sampling intervals at location 3 and five of six sampling intervals at location 4 (Tables 3.7 and 3.8). One likely explanation for the differences between locations 1 and 3 is differences in root development during the early growing season each year. At Suffolk, VA (location 1) in 2013, May and June had 29.8 cm of rainfall, while May and June in 2014 (location 3) received 15.2 cm (Mehl and Masters, 2015).

The rainfall totals in 2013 may have limited root growth at greater depths resulting in a proliferation of roots in the 5x5 banded zone. In 2014, it is speculated that cotton roots were not hindered by excess moisture and were able to access the nutrients in the deep placement bands earlier which affected plant heights. Applications of plant growth regulator (PGR) followed extension recommendations based on growth at all locations. At location 1 the plant growth regulator, mepiquat pentaborate, occurred during 7, 9, and 12 weeks after planting, likely reducing plant height reponses in late sampling intervals. At location 3 PGR applications were made during 9 and 12 weeks after planting, not influencing plant heights that ceased after 8 weeks after planting. The dates of PGR applications at locations 2 and 4 are unknown.

Previous research supports the observations in this study that environmental conditions affect the efficacy of different early season nutrient management strategies on early season growth of cotton. Over the row placement of ammonium polyphosphate produced taller plants than 5x5 banded during a two year study in South Carolina (Toler et al., 2004). Studies in Tennessee and Louisiana resulted in 5x5 banding of 11-37-0 increasing plant heights over in-furrow and broadcast applications in conventionally tilled cotton (Howard and Hutchinson, 1997).

Total number of nodes was significantly impacted by nutrient delivery system at locations 1 and 3, with the unfertilized controls having the fewest total nodes (Tables 3.9 and 3.10). Nutrient management system did not affect total number of nodes at locations 2 and 4 (Tables 3.10 and 3.12). In a three year study 11-37-0 applied in-furrow at a rate of 4.4 kg N ha^{-1} and 6.5 kg P ha^{-1} also had no significant effects on total number of nodes (Pettigrew and Molin, 2014). Interestingly, Osmond et al. (2006) evaluated 30 cotton sites testing very high in soil test P, finding number of nodes at first bloom greater for N only starter than starter containing N and

P. The response to total nodes indicates that N fertility has a greater influence on node development compared to P and K fertility levels. Locations 2 and 4 received side-dress N and resulted in fewer early season plant growth differences among nutrient management systems whereas location 1 and 3 did not received side-dress N.

Nodes above white flower counts were significantly different among nutrient delivery systems for all sampling intervals at location 1, with unfertilized controls having the fewest NAWF during all sampling intervals (Table 3.9). The unfertilized control had significantly fewer NAWF than all nutrient management systems during the tenth and eleventh weeks after planting (Table 3.9). Nodes above white flower were not significantly different among nutrient management systems during any sampling interval at location 2 (Table 3.10). Significant NAWF differences were observed at two out of three sampling intervals, and unfertilized control had the fewest NAWF at all sampling intervals for location 3 (Table 3.11). Contradictory to findings at other locations, the unfertilized control had the greatest NAWF numerically at all sampling intervals at location 4 (Table 3.12). Osmond et al. (2006) found no differences in NAWF when comparing starter fertilizers containing N with and without P. Nodes above white flower is a measure of maturity, it would be expected for unfertilized controls to have the fewest NAWF due to development ceasing earlier than fertilized treatments. The lack of differences observed when side-dress N was applied indicates that N was the most limiting nutrient at locations 2 and 4 during the study.

3.4.1.2 Petiole Phosphorus

Locations 1 and 3 had unfertilized checks that received no side-dress N, while locations 2 and 4 had unfertilized checks receiving only side-dress N. This difference had large implications on petiole P, as petiole P concentrations appear to be connected to nitrogen status. At locations 1 and 3 unfertilized checks had significantly higher P concentrations than all other nutrient management systems in 17 out of 18 sampling intervals collectively (Fig. 3.2a and 3.2c). At location 2 unfertilized checks had the lowest petiole P concentrations in six out of nine sampling intervals (Fig 3.2b). All systems including the unfertilized control resulted in similar P concentrations at location 4 (Fig. 3.2d).

At locations 1 and 3 petiole nitrate concentrations dropped rapidly in the first few weeks of bloom, with unfertilized controls having the lowest petiole nitrate-N concentrations (data not shown). At these two locations nitrogen deficient plants inflated measured P concentrations, thought to be due to plants being smaller in size increasing the relative concentration of P measured in the petioles. All petioles measured above 800 mg kg^{-1} P during the first week of bloom, a sufficiency range proposed in Arkansas and Georgia.by (Mitchell and Baker, 2000)

Petiole Potassium

Nutrient management system had little effect on petiole K levels at locations 1 and 4 (Fig. 3a and 3d). A greater range in values was recorded at location 2 where the unfertilized control consistently had the lowest levels, and system was significant at three out of nine sampling intervals (Fig. 3.3c).

Location 3 produced the greatest variability throughout the bloom period in respect to nutrient management system and potassium levels in petioles, significantly different during six of the nine sampling intervals (Fig. 3.3c). The liquid starter treatments resulted in significantly higher petiole potassium than the unfertilized control during the first, third, fifth, sixth, and seventh weeks of bloom, while the same was true for the broadcast control during the first and fifth week of bloom (Fig. 3.3c). During the ninth week of bloom the liquid starter control produced significantly higher petiole K levels than the unfertilized control, 100% 5x5 band, and the 100% deep placement treatments, and the broadcast agronomic control had significantly higher petiole K levels than 100% 5x5 band and the 100% deep placement treatments (Fig. 3.3c). As both of these treatments had K broadcast applied, these results indicate that when soil moisture was optimal, broadcasting K may be more efficient as K moves to the plant roots via mass flow and a greater number of plant roots are able to intercept and utilize K compared to banded applications. Other studies found that both broadcast K alone or broadcasted/banded combinations of K consistently increased K over three years; however when moisture was lacking 5x5 banded K rate linearly increased petiole K concentrations at one site (Adeli and Varco, 2002).

3.4.1.3 Lint Yield

The only significant lint yield differences observed between nutrient delivery systems occurred at locations 1 and 3, where all systems had higher lint yields than the unfertilized control. (Fig. 3.4a and 3.4c). Unfertilized controls received side-dress N at locations 2 and 4, while no fertilization occurred throughout the season at locations 1 and 3. Nutrient management systems at location 4 were not significantly different in lint yield, however the unfertilized control had the lowest lint yield (Fig. 3.4d). In opposition the unfertilized control produced the highest lint yields numerically at location 2. The results at locations 2 and 4 indicated that the sites were N limited and once N was applied very little response to P and K was observed.

These results support N being the most limiting nutrient in cotton production systems where soil test P and K levels are medium to high (Table 3.2). Our results affirm the importance of N in cotton production, which has been well documented by others. Rashidi and Seilsepour (2011) evaluated N rate effect on cotton, finding 200 kg N ha^{-1} to increase seed cotton yield by 19.6%. Saleem et al. (2010) found nitrogen fertilization to have significant effect on seed cotton yield, with 120 kg N ha^{-1} producing 3,002.4 kg and the control yielded 2,716 kg of seed cotton. When N rate was tested over six sites in Tennessee, 169-186 kg N ha^{-1} produced the highest lint yields with optimal rate differing by location (Zhou and Yin, 2014).

3.4.2 Phosphorus and Potassium Rate by Placement

3.4.2.1 In-season Plant Growth Measurements

Plant heights at locations 1 and 3 were the most responsive to P and K rate and placement. At location 1, 5x5 banding produced significantly taller plants than deep placement for the last three out of six sampling intervals (Table 3.13). At location 3, P and K rate significantly affected plant heights at five out of six sampling intervals, with 150% rates producing the tallest plants (Table 3.15). Deep placement and 5x5 banding had no effect on silt loam soil over 3 years, but starters increased the height of plants on a sandy loam in all 3 years, with 5x5 banding generally producing tallest plants (Touchton et al., 1986). This contradicts our results as locations 2 and 4 were sandy loam sites having only one of six intervals significantly affected by placement, as deep placement produced tallest plants (Tables 3.14 and 3.16).

Total number of nodes and NAWF were not affected by P and K rate and placement at locations 3, and 4. At location 1, 5x5 banding produced more nodes at one of two sampling intervals, and less NAWF at 1 of 4 sampling intervals (Table 3.13). At this location maturity rate, measured by NAWF, seemed to be influenced more by P and K rate than placement, as P and K rate significantly impacted NAWF at two of four sampling intervals with 150% rate producing the fewest (Table 3.13). At location 2 total number of nodes was not impacted by P and K rate and placement, though NAWF were significantly impacted by rate at one of four sampling intervals (Table 3.14).

3.4.2.2 Petiole Nutrient Analyses

Petiole P and K concentrations followed the same trends as those observed in nutrient management system analysis. During the first week of bloom at location 1, petiole phosphorus was increased by 5x5 banding and the 50% rate (Table 3.17). Banding nutrient in a 5x5 placement may promote increased P uptake early in the growing season, until roots are given time to explore nutrients at deeper depths. At location 2, petiole P concentrations were affected by placement during the first week of bloom and rate*placement interaction during the fifth; while K concentrations were significantly affected by rate during the first and seventh weeks of bloom (Table 3.18).

At location 3, the interaction for rate*placement was significant for petiole P during the sixth week of bloom, and first and sixth week of bloom for petiole K (Table 3.15). The Tukey-Kramer means separation procedure did not separate out the means for each treatment during these sampling intervals and no clear trend existed to the response that could be explained biologically. Only two sampling intervals were found to be significant for petiole K at location 4 with placement being significant during the ninth week of bloom and P and K rate significant during the sixth week of bloom (Table 3.20). The rate*placement interaction was significant for petiole P during the seventh and eight weeks of bloom, while rate alone was significant during the fourth and sixth weeks of bloom (Table 3.20).

3.4.2.3 Lint Yield

Lint yield was not affected by P and K application rates at locations 1 or 2 during 2013 (Fig. 6). At location 1, lint yields were increased with the 5x5 band placement compared to the deep placement of P and K (Fig. 3.5). The 5x5 band produced increased lint yields of 2,244 kg lint ha^{-1}, while deep placement yielded 2,082 kg lint ha^{-1} respectively at location 1. At location 2, lint yields with the 5x5 band were not significantly different from the deep placement system, however there was a 91 kg lint difference between the two treatments, with 1,494 kg lint ha^{-1} and 1,403 kg lint ha^{-1}, respectively.

During 2014, the opposite placement effect was observed, as deep placement of P and K produced higher yields than 5x5 banding. At location 3, deep placement had significantly higher yields than the 5x5 banding of P and K with 2,212 kg lint ha^{-1} and 2,025 kg lint ha^{-1}, respectively (Fig. 3.5). At location 4, deep placement increased lint yields numerically over 5x5 banding, as deep placement produced 1,212 kg lint ha^{-1} and 5x5 band 1,115 kg lint ha^{-1}. Previously mentioned environmental differences between 2013 and 2014 growing seasons are likely the cause of discrepancy in placement results over years, as roots were able to access deeper placed nutrients in 2014.

No statistically significant differences in lint yield over P and K application rates were detected at any location, however, locations 2 and 3 had numerical increases in lint yield as P and K application rates were increased to 150% (Fig. 3.6). At locations 1, 3, and 4, the 50% P and K application rate produced the lowest lint yields.

3.4.2.4 Conclusion

One of the key findings from this study was the relationship between petiole P and N status. Results consistently showed that unfertilized controls receiving no N had increased petiole P concentrations compared to treatments receiving P, which could be attributed to limited N restricting growth. Plant heights were consistently lower in the unfertilized controls and these smaller plants influenced the P concentrations measured in petioles collected. This illustrates the importance of monitoring crop N status, when petiole testing for P. In addition many of the responses to nutrient management system were distinctly different between the two locations where the unfertilized controls received side-dress N and the two where they did not. These results support that N has a greater impact on growth and development than P and K when soil test P and K levels are medium to high. Also, environmental conditions affected lint yield responses to deep placement and 5x5 banded P and K. At Suffolk, VA in 2013, May and June had 50% more rainfall numerically than May and June in 2014, which may have restricted root growth at greater depths resulting in a proliferation of roots in the 5x5 banded zone. In 2014, it is hypothesized that cotton roots were not hindered by excess moisture, and were able to access the nutrients in the deep placement bands earlier. Greatest lint yields were produced from 5x5 banded P and K in 2013, and deep placement in 2014. More research is required to evaluate the most effective P and K placement in upland cotton production.

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Fig. 3.1: Deep placement fluid fertilizer delivery system used in a P and K fertilizer rate and placement cotton study.

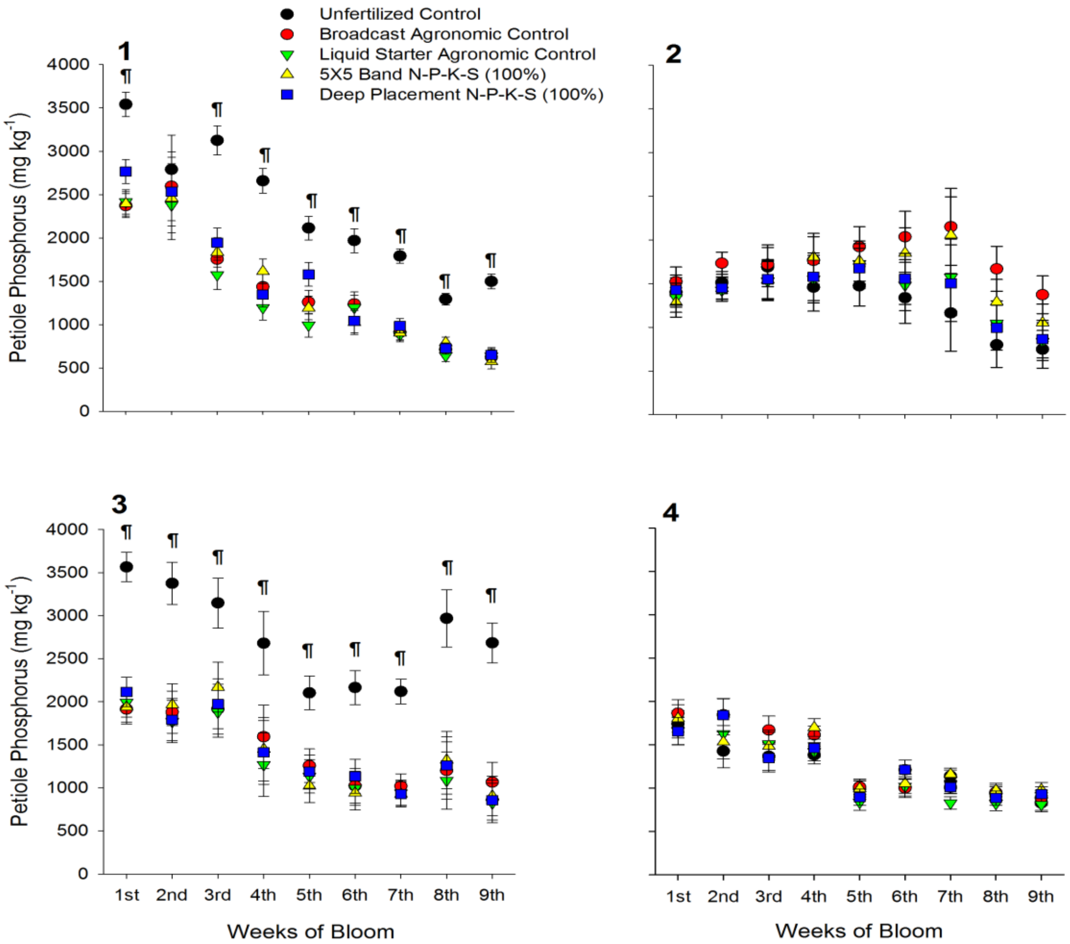

Fig. 3.2: Petiole phosphorus concentrations in cotton petioles from the 4th leaf from the top using different nutrient application management systems during the 1st through nine weeks of bloom at locations of a P and K fertilizer rate and placement cotton study, 1 (A), 2 (B), 3 (C), and 4 (D). (¶ Indicates ANOVA was significant at $\alpha = 0.1$ for that sampling interval).Standard error is indicated by bars for each treatment.

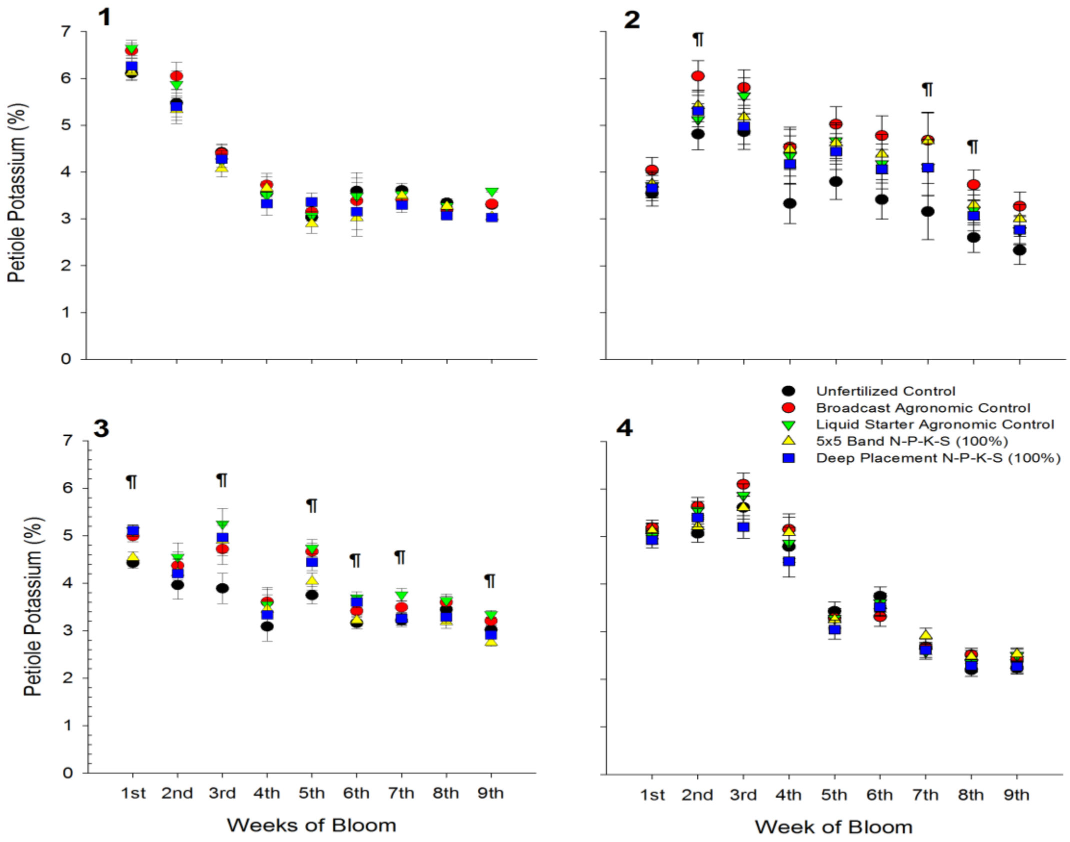

Fig. 3.3: Petiole potassium levels in cotton petioles from the 4th leaf from the top using different nutrient application management systems during the 1st through nine weeks of bloom at locations of a P and K fertilizer rate and placement cotton study, 1 (A), 2 (B), 3 (C), and 4 (D). (¶ Indicates ANOVA was significant at α = 0.1 for that sampling interval). Standard error is indicated by bars for each treatment.

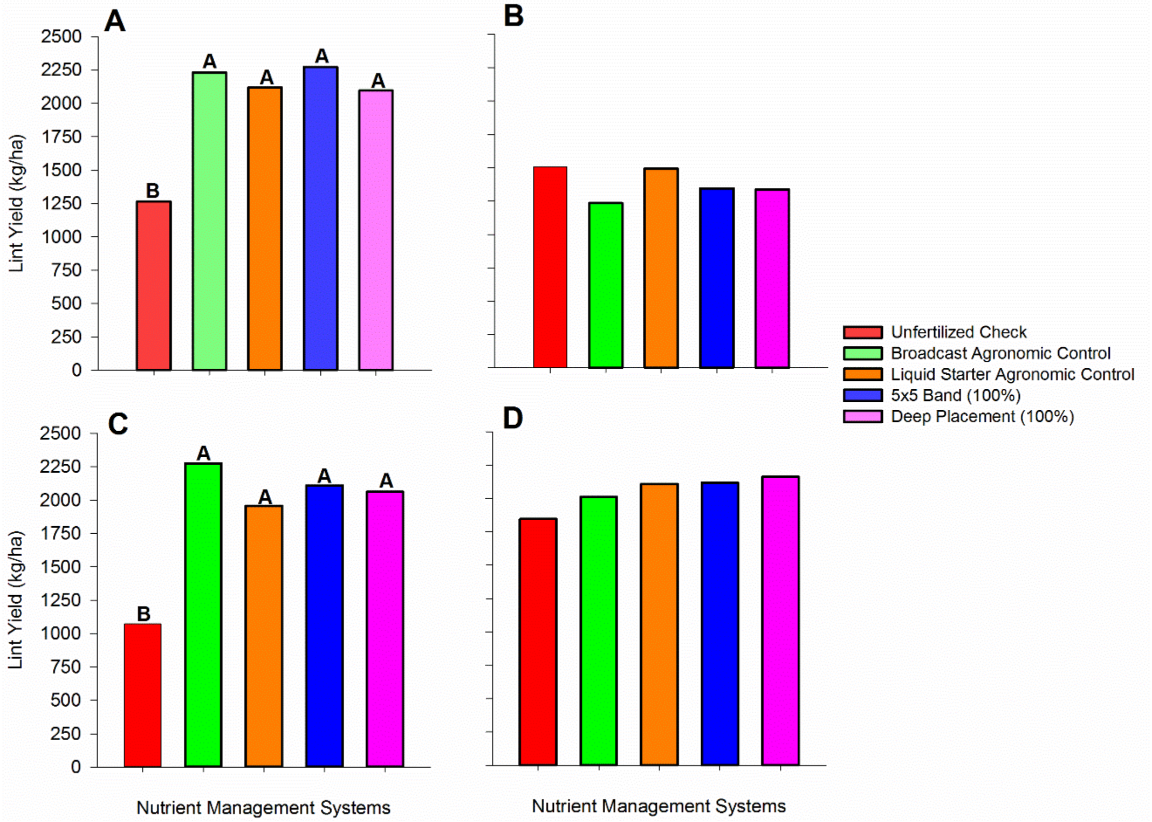

Fig. 3.4: Effect of nutrient management system on cotton lint yields at location 1(A), 2(B), 3(C), and 4(D) of a P and K fertilizer rate and placement cotton study. Columns with the same letter are not significantly different for means separation at α = 0.10. Absence of letters above bars indicates ANOVA was not significant.

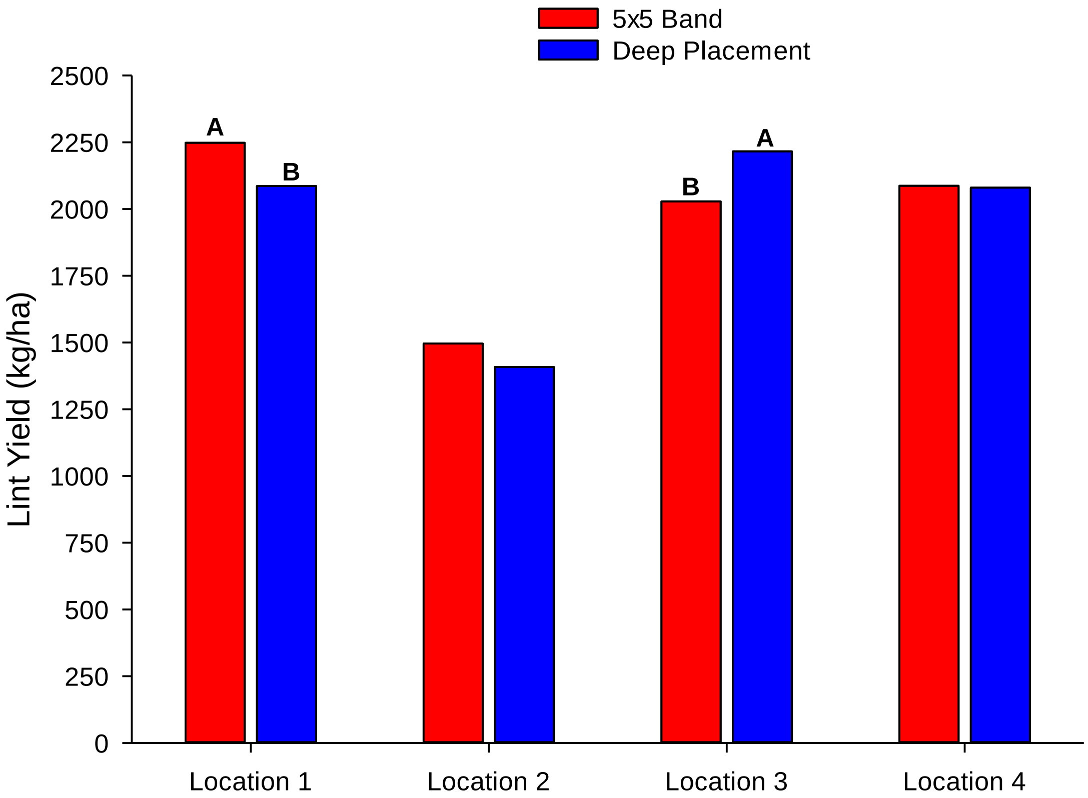

Fig. 3.5: Effect of phosphorus and potassium placement on cotton lint yields at all locations of a P and K fertilizer rate and placement cotton study. Columns with the same letter are not significantly different for means separation at α = 0.10. Absence of letters above bars indicates ANOVA was not significant.

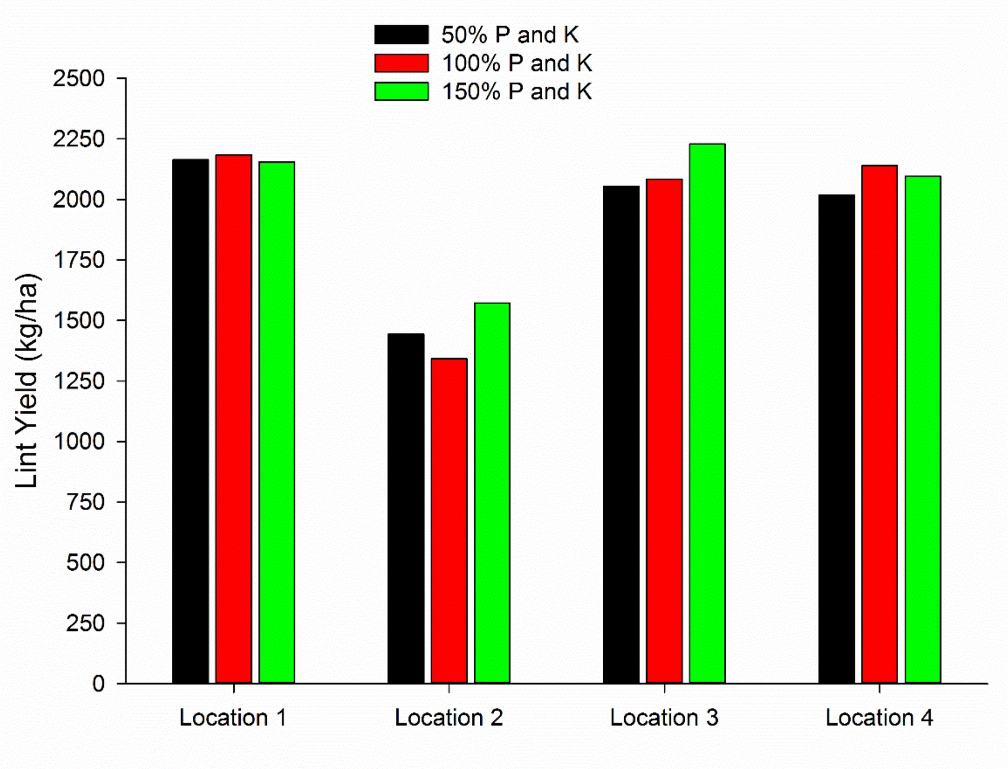

Fig. 3.6: Effect of phosphorus and potassium application rate on cotton lint yields at all locations of a P and K fertilizer rate and placement cotton study. Absence of letters above bars indicates ANOVA was not significant.

Table 3.1: Soil characteristics for all locations of a P and K fertilizer rate and placement cotton study.

Location #	**Location**	**Series**	**Type**	**Family**
1	Suffolk, VA	Eunola	loamy sand	fine-loamy, siliceous, semiactive, thermic Aquic Hapludults
2	Lewiston, NC	Rains	sandy loam	fine-loamy, siliceous, semiactive, thermic Typic Paleaquults
3	Suffolk, VA	Eunola	loamy sand	fine-loamy, siliceous, semiactive, thermic Aquic Hapludults
4	Lewiston, NC	Norfolk	sandy loam	fine-loamy, kaolinitic, thermic Typic Kandiudults

Table 3.2: Mehlich I extractable phosphorus and potassium at 0-8, 8-15, 15-23, 23-31 cm depths for all locations of a P and K fertilizer rate and placement cotton study.

	1		**2**		**3**		**4**	
	P	**K**	**P**	**K**	**P**	**K**	**P**	**K**
Depth(cm.)	--mg kg^{-1}--							
0-8	49 (H+) †	99 (H-)	30 (H)	126 (H)	39 (H)	106 (H)	15 (M+)	81 (M+)
8-15	31 (H)	86 (M+)	18 (H-)	59 (M)	26 (H-)	98 (H-)	12 (M)	60 (M)
15-23	20 (H-)	73 (M)	13 (M)	37 (L+)	17 (M+)	76 (M+)	9 (M-)	48 (M-)
23-31	19 (H-)	68 (M)	7 (M-)	33 (L+)	7 (M-)	101 (H-)	3 (L)	42 (M-)

† Indicates the soil test level based on Virginia's soil test calibration

Table 3.3: Treatment list for different nutrient management strategies and application rates for all locations of a P and K fertilizer rate and placement cotton study.

Trt	**Placement**	**Description**
1	Unfertilized Control	No P or K Fertilization
2	Broadcast Agronomic Control	P + K Broadcast – Soil test recommendation†
3	Starter Agronomic Control	112 kg ha^{-1} ‡ of 10-34-0 in 5x5 band + Remaining P+K broadcast
4	5x5 Band	50%P + 50%K §
5	5x5 Band	100%P + 100%K
6	5x5 Band	150%P + 150%K
7	Deep Placement	50%P + 50%K
8	Deep Placement	100%P + 100%K
9	Deep Placement	150%P + 150%K

†Recommended nutrient application rates applied based on Mehlich 1 extractable phosphorus and potassium and Virginia Cooperative Extension Recommendations

‡ 112 kg ha^{-1} of 10-34-0 is the recommended rate for cotton placed in a 5x5 band at planting in by North Carolina State University Cooperative Extension.

§Percentages represent the proportion of recommended nutrient application rates applied based on Mehlich 1 extractable phosphorus and potassium and Virginia Cooperative Extension Recommendations.

Table 3.4: Strip-tillage, planting, and harvesting dates for all locations of a P and K fertilizer rate and placement cotton study.

Location	Strip-tillage	Planted	Harvested
1	5/7/2013	5/10/2013	10/21/2013
2	5/16/2013	5/30/2013	11/19/2013
3	5/6/2014	5/12/2014	11/13/2014
4	5/7/2014	5/20/2014	11/4/2014

Table 3.5: Early season plant height of cotton grown under different nutrient management systems at location 1 of a P and K fertilizer rate and placement cotton study.

Treatment	Plant Height					
	4th†	5th	6th	7th	8th	9th
	------------------------------cm.-----------------------------					
Unfertilized Check	12.2	18.8 c ‡	23.9 c	33.5 d	45.7 c	55.9 b
Broadcast Control	12.2	21.6 ab	26.7 bc	39.1 c	56.9 b	75.2 a
Starter Control	12.7	24.4 a	28.2 ab	45.2 ab	61.2 ab	79.8 a
5 x 5 Band (100%)	13.2	23.9 ab	30.7 a	47.2 a	65.8 a	81.3 a
Deep Placement (100%)	12.5	22.1 ab	28.7 ab	42.9 bc	60.7 b	78.5 a

†Week after Planting

‡ Values with the same letter are not significantly different for means separation at α=0.1. Absence of letters indicates ANOVA was not significant.

Table 3.6: Early season plant height of cotton grown under different nutrient management systems at location 2 of a P and K fertilizer rate and placement cotton study.

Treatments	Plant Height		
	9th†	10th	11th
	------------cm.------------		
Unfertilized Check	31.8‡	49.5	62.2
Broadcast Control	30.7	49.5	66.8
Starter Control	33.5	51.1	66.0
5 x 5 Band (100%)	31.5	50.8	67.6
Deep Placement (100%)	32.5	51.3	66.3

†Week after Planting

‡ Values with the same letter are not significantly different for means separation at α=0.1. Absence of letters indicates ANOVA was not significant.

Table 3.7: Early season plant height of cotton grown under different nutrient management systems at location 3 of a P and K fertilizer rate and placement cotton study.

Nutrient Systems	Plant Height					
	3rd†	4th	5th	6th	7th	8th
	----------------------------cm.----------------------------					
Unfertilized Check	8.43 b ‡	14.8 b	25.5 c	37.1 b	44.6 b	57.1 b
Broadcast Control	9.10 ab	17.9 ab	26.1 bc	44.9 ab	59.0 a	74.2 a
Starter Control	9.10 ab	19.2 a	30.6 ab	48.9 a	62.1 a	76.3 a
5 x 5 Band (100%)	9.73 a	19.3 a	31.7 a	49.5 a	62.4 a	77.8 a
Deep Placement (100%)	9.13 ab	18.93 a	31.2 a	49.5 a	62.9 a	78.3 a

†Week after Planting

‡ Values with the same letter are not significantly different for means separation at $\alpha = 0.1$. Absence of letters indicates ANOVA was not significant.

Table 3.8: Early season plant height of cotton grown under different nutrient management systems at location 4 of a P and K fertilizer rate and placement cotton study.

Nutrient Systems	Plant Height					
	3rd†	4th	5th	6th	7th	8th
	----------------------------cm.----------------------------					
Unfertilized Check	9.0 b ‡	16.8 b	26.5 c	38.7 b	50.8 b	71.5 b
Broadcast Control	10.5 a	19.1 a	30.7 a	45.3 a	59.0 a	80.9 a
Starter Control	10.6 a	19.6 a	30.6 ab	46.8 a	59.9 a	81.6 a
5 x 5 Band (100%)	10.3 a	18.7 a	28.2 bc	44.2 a	59.9 a	81.0 a
Deep Placement (100%)	10.2 ab	19.7 a	30.8 a	46.9 a	61.2 a	84.7 a

†Week after Planting

‡ Values with the same letter are not significantly different for means separation at $\alpha = 0.1$. Absence of letters indicates ANOVA was not significant.

Table 3.9: Total nodes and NAWF for cotton grown under different nutrient management systems at location 1 of a P and K fertilizer rate and placement cotton study.

Treatment	**Total Nodes**		**Nodes Above White Flower (NAWF)**			
	8th†	9th	10th	11th	12th	13th
Unfertilized Check	9.8 b ‡	10.1 b	6.6 b	4.8 b	3.2 b	1.8 b
Broadcast Control	10.5 ab	11.7 a	7.7 a	6.3 a	4.5 a	2.6 ab
Starter Control	11.1 a	11.9 a	7.3 a	5.8 a	4.0 ab	2.3 ab
5 x 5 Band (100%)	11.5 a	11.6 a	7.4 a	5.8 a	4.2 ab	2.8 a
Deep Placement (100%)	11.2 a	11.4 a	7.9 a	6.0 a	4.1 ab	3.0 a

†Week after Planting

‡ Values with the same letter are not significantly different for means separation at α=0.1. Absence of letters indicates ANOVA was not significant.

Table 3.10: Total nodes and NAWF for cotton grown under different nutrient management systems at location 2 of a P and K fertilizer rate and placement cotton study.

Treatments	**Total Nodes**		**Nodes Above White Flower**			
	9th†	10th	11th	12th	13th	14th
Unfertilized Check	9.9 ‡	11.3	6.8	6.4	5.7	3.1
Broadcast Control	9.8	11.4	7.6	7.5	6.7	4.4
Starter Control	9.7	11.0	7.5	6.7	5.8	3.8
5 x 5 Band (100%)	10.3	11.4	7.7	7.0	6.3	3.6
Deep Placement (100%)	10.5	11.3	7.5	7.4	6.3	3.9

†Week after Planting

‡ Values with the same letter are not significantly different for means separation at α = 0.1. Absence of letters indicates ANOVA was not significant.

Table 3.11: Total nodes and NAWF for cotton grown under different nutrient management systems at location 3 of a P and K fertilizer rate and placement cotton study.

Nutrient Systems	**Nodes**	**Nodes Above White Flower**		
	9th†	9th	10th	11th
Unfertilized Check	10.4 b‡	5.4	4.1 b	2.5 b
Broadcast Control	11.5 ab	5.9	5.3 a	4.0 a
Starter Control	11.9 a	6.1	5.0 ab	3.3 ab
5 x 5 Band (100%)	11.6 ab	6.3	5.3 a	3.7 a
Deep Placement (100%)	11.9 a	6.3	5.4 a	3.4 a

†Week after Planting

‡ Values with the same letter are not significantly different for means separation at α = 0.1. Absence of letters indicates ANOVA was not significant.

Table 3.12: Total nodes and NAWF for cotton grown under different nutrient management systems at location 4 of a P and K fertilizer rate and placement cotton study.

Nutrient Systems	**Nodes**	**Nodes Above White Flower**			
	9th[†]	9th	10th	11th	12th
Unfertilized Check	12.4	7.5	7.0 a[‡]	5.7	4.5
Broadcast Control	12.3	7.5	6.6 ab	5.3	4.3
Starter Control	13.1	7.3	6.4 b	5.1	3.8
5 x 5 Band (100%)	12.2	7.3	6.7 ab	5.1	4.5
Deep Placement (100%)	12.8	7.3	6.8 ab	5.2	4.4

†Week after Planting

‡ Values with the same letter are not significantly different for means separation at α=0.1. Absence of letters indicates ANOVA was not significant.

Table 3.13: Analysis of variance results for the model effects of phosphorus (P) and potassium (K) application rates and placement on early season plant height, total nodes, and nodes above white flowers (NAWF) at location 1 of a P and K fertilizer rate and placement cotton study.

Model Effect	Plant Height						Total Nodes		Nodes Above White Flower			
	4th†	5th	6th	7th	8th	9th	8th	9th	10th	11th	12th	13th
Placement	NS‡	NS	NS	*	*	*	*	NS	NS	*	NS	NS
Rate	NS	NS	NS	*	NS	NS	NS	NS	*	NS	*	NS
Rate*Placement	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

†Week after planting

‡ Indicates that the model effect p-value was not significant at α = 0.1

*Indicates that the model effect p-value was significant at α = 0.1

Table 3.14: Analysis of variance results for the model effects of phosphorus (P) and potassium (K) application rates and placement on early season plant height, total nodes, and nodes above white flowers (NAWF) at location 2 of a P and K fertilizer rate and placement cotton study.

Model Effects	Plant Height			Total Nodes		Nodes Above White Flower			
	9th†	10th	11th	9th	10th	11th	12th	13th	14th
Placement	NS‡	NS	NS	NS	NS	NS	NS	NS	NS
Rate	*	NS	NS	NS	NS	*	NS	NS	NS
Rate*Placement	NS	NS	NS	NS	NS	NS	NS	NS	NS

†Week after planting

‡ Indicates that the model effect p-value was not significant at α = 0.1

* Indicates that the model effect p-value was significant at α = 0.1

Table 3.15: Analysis of variance results for the model effects of phosphorus (P) and potassium (K) application rates and placement on early season plant height, total nodes, and nodes above white flowers (NAWF) at location 3 of a P and K fertilizer rate and placement cotton study.

Model Effect	**Plant Height**						**Nodes**	**Nodes Above White Flower**		
	3rd†	4th	5th	6th	7th	8th	9th	9th	10th	11th
Placement	NS‡	NS	NS	NS	*	NS	NS	NS	NS	NS
Rate	*	*	*	*	*	NS	NS	NS	NS	NS
Rate*Placement	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

†Week after planting

‡ Indicates that the model effect p-value was not significant at α = 0.1

*Indicates that the model effect p-value was significant at α = 0.1

Table 3.16: Analysis of variance results for the model effects of phosphorus (P) and potassium (K) application rates and placement on early season plant height, total nodes, and nodes above white flowers (NAWF) at location 4 of a P and K fertilizer rate and placement cotton study.

Model Effect	**Plant Height**						**Nodes**	**Nodes Above White Flower**			
	3rd†	4th	5th	6th	7th	8th	9th	9th	10th	11th	12th
Placement	NS‡	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rate*Placement	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Week after planting

‡ Indicates that the model effect p-value was not significant at α = 0.1

* Indicates that the model effect p-value was significant at α = 0.1

Table 3.17: Analysis of variance results for the model effects of phosphorus (P) and potassium (K) application rates and placement on phosphorus and potassium concentrations of petioles from the 4th leaf from the top during the first nine weeks of bloom at location 1 of a P and K fertilizer rate and placement cotton study.

Model Effect	**Petiole Phosphorus During First Nine Weeks of Bloom**								
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
Placement	*	NS†	NS	NS	NS	NS	NS	NS	NS
Rate	*	*	NS	NS	NS	NS	NS	NS	NS
Rate*Placement	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Petiole Potassium During First Nine Weeks of Bloom								
Placement	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rate*Placement	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Indicates that the model effect p-value was not significant at α = 0.1
* Indicates that the model effect p-value was significant at α = 0.1

Table 3.18: Analysis of variance results for the model effects of phosphorus (P) and potassium (K) application rates and placement on phosphorus and potassium concentrations of petioles from the 4th leaf from the top during the first nine weeks of bloom at location 2 of a P and K fertilizer rate and placement cotton study.

Model Effect	**Petiole Phosphorus During First Nine Weeks of Bloom**								
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
Placement	*	NS†	NS	NS	NS	NS	NS	NS	NS
Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rate*Placement	NS	NS	NS	NS	*	NS	NS	NS	NS
	Petiole Potassium During First Nine Weeks of Bloom								
Placement	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rate	*	NS	NS	NS	NS	NS	*	NS	NS
Rate*Placement	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Indicates that the model effect p-value was not significant at α = 0.1
* Indicates that the model effect p-value was significant at α = 0.1

Table 3.19: Analysis of variance results for the model effects of phosphorus (P) and potassium (K) application rates and placement on phosphorus and potassium concentrations of petioles from the 4th leaf from the top during the first nine weeks of bloom at location 3 of a P and K fertilizer rate and placement cotton study.

Model Effect	**Petiole Phosphorus During First Nine Weeks of Bloom**								
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
Placement	NS †	NS	NS	NS	NS	NS	NS	NS	NS
Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rate*Placement	NS	NS	NS	NS	NS	*	NS	NS	NS
	Petiole Potassium During First Nine Weeks of Bloom								
Placement	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rate*Placement	*	NS	NS	NS	NS	*	NS	NS	NS

† Indicates that the model effect p-value was not significant at α = 0.1

* Indicates that the model effect p-value was significant at α = 0.1

Table 3.20: Analysis of variance results for the model effects of phosphorus (P) and potassium (K) application rates and placement on phosphorus and potassium concentrations of petioles from the 4th leaf from the top during the first nine weeks of bloom at location 4 of a P and K fertilizer rate and placement cotton study.

Model Effect	**Petiole Phosphorus During First Nine Weeks of Bloom**								
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
Placement	NS †	NS	NS	NS	NS	NS	NS	NS	NS
Rate	NS	NS	NS	*	NS	*	NS	NS	NS
Rate*Placement	NS	NS	NS	NS	NS	NS	*	*	NS
	Petiole Potassium During First Nine Weeks of Bloom								
Placement	NS	NS	NS	NS	NS	NS	NS	NS	*
Rate	NS	NS	NS	NS	NS	*	NS	NS	NS
Rate*Placement	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Indicates that the model effect p-value was not significant at α = 0.1

* Indicates that the model effect p-value was significant at α = 0.1

Conclusion

Virginia is the northern most state in the United States cotton belt, with cotton production concentrated in the southeast portion of the Commonwealth. This geographical cotton production area accumulates less heat units than other cotton-growing areas in the U.S., resulting in a shortened growing season. Stimulating optimal growth through nutrient management is key to maximizing yields in Virginia’s climate.

Petiole and tissue S and B concentrations were more responsive than K concentrations at the rates of side-dress S, B and K applied with N during the study. Pre-plant K applied to soil test recommendations, along with sites testing medium to high for K, limited K response at each location. Boron was applied at 1.5 kg B ha^{-1} with the current potassium sulfate coated urea (KSCU) formulation that included B and met the recommended rate for Virginia and North Carolina (Reiter, 2013; Crozier et al., 2013). Supplying recommended rates of B resulted in increases in leaf B concentrations in 5 of 6 sampling intervals. The amount of S applied in the current formulation (5.6 kg S ha^{-1}) was below current season-long S recommendations in Virginia, 22.5 kg S ha^{-1} (Reiter, 2013). Changing the current formulation of KSCU to increase S application rates closer to 22.5 kg S ha^{-1} S may produce a greater likelihood of S tissue and lint yield response. Lint yields were not significantly affected by side-dress S, B, and K at any location. Lint yield for KSCU formulations were similar to bulk blended granular urea and potassium sulfate, but KSCU has the advantage of supplying N, K, S, and B with the application of one product. More research is needed to evaluate KSCU formulations which have the ability to supply greater application rates of S in upland cotton systems. Environments where soil K levels are lower than sites tested in this study will be needed to evaluate the efficacy of applying K with side-dress N.

Nitrogen had a greater impact on growth and development of upland cotton than P and K when soils tested medium to high in Mehlich I extractable P and K. The unfertilized control consistently had shorter plants representing restricted growth across locations. When no fertilizer was applied, petiole P concentrations were significantly higher compared to those receiving N and P. These results affirm that when using petiole testing to monitor in-season P status, N status must also be evaluated before making inferences about P status during the bloom period. Lint yield was significantly greater for all treatments receiving P and K compared to unfertilized controls when no N was applied throughout the season. No lint yield differences among nutrient management systems occurred when side-dress N was applied. Results support that N is often the most limiting nutrient in cotton production and N management and supply must be at the forefront of nutrient management decisions to maximize lint yields.

At location 2 of the P and K study early season sand-burn injury from a high-wind storm delayed maturity and reduced response to P and K nutrient management. These stressful environmental conditions provide data on upland cotton nutrient status under early season stress. Results of the nutrient management system of P and K study indicate that deep placement under the row during strip tillage and banding 5 cm besides the seed and 5 cm below the seed produce could be done effectively and produce lint yields similar to current practices. In the same study environmental conditions affected response to P and K placement. In 2013, 50% more rainfall was measured in May and June than of 2014 in Suffolk, VA. Subsequently 5x5 banding of P and K produced highest yields at both 2013 locations, while deep placement produced greatest amounts of lint at 2014 locations. Also 2014 locations generally had tallest plant heights from deep placement of P and K compared to 5x5 banding. At location 1 in 2013 5x5 banding produced tallest plants at 5 of 6 sampling intervals. More research is required to evaluate the most consistently effective P and K placement in upland cotton production.

These studies support that Virginia cotton growers should apply pre-plant K to soil test recommendations, and continue applying S and B at recommended rates. Furthermore, due to influence on growth and development N should be a primary area of focus for cotton growers, and N status should be considered when petiole testing for P.