Foliar Fertilization of Soybean in North Carolina and Southeastern Virginia

Dylan Thomas Lilley

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Dr. David L. Holshouser, Chair

Dr. Rachel A. Vann

Dr. Mark S. Reiter

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Abstract

The purpose of this project was to determine the need for foliar fertilization of soybean. The objectives for this research were (1) to determine soybean plant tissue and yield response to foliar fertilization with commercially sold products and (2) to evaluate profitability of applying such products. Experiments were conducted during the 2019 growing season at four locations in North Carolina and southeast Virginia. Six foliar fertilizers containing formulations of macro, secondary, and micronutrients were applied to R3-stage soybean and compared to an untreated control. Plant tissue samples were collected immediately before application and two weeks afterward to measure the change in tissue nutrient concentration. FertiRain significantly increased iron plant tissue concentration by 8% at two locations. Sure-K significantly reduced loss of nitrogen and phosphorus in the tissue by 7% at one location. Smart B-Mo significantly increased boron plant tissue concentration by 41% at three locations. Smart Quatro increased zinc plant tissue concentration by 27% at one location. HarvestMore UreaMate increased copper tissue concentration by 13% at three locations and zinc by 14% at another, but reduced copper and potassium plant tissue concentration by 17% and 10%, respectively, at one location. Despite plant tissue concentration increases of select nutrients, none of the foliar fertilizers affected yield at any location; therefore, profit decreased by $3.82 to $22.11 per acre, depending on cost of the product at the applied rate. Despite the lack of yield response to foliar fertilizers tested, soybean may respond positively under different environments, hence further research is necessary to determine the need for foliar fertilization.

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Introduction

Soybean (*Glycine Max*) is a vital part of the economy for both North Carolina (NC) and Virginia (VA). In 2019 there were 1,540,000 acres of soybean planted in NC and 570,000 acres planted in VA (USDA-NASS, 2019). In terms of value of production in dollars in 2019, soybean ranked first in NC ($468,160,000) and third in VA ($167,552,000) behind hay and corn grown for grain and silage among all other commodities produced. Increasing soybean yield is a main component of profitability, therefore receives great attention from producers. Soybean yield in the United States has averaged around 46.37 bu/A for the last decade, representing an approximate fourfold increase since 1924 (USDA-NASS, 2019). Yields in NC and VA from 1990-1999 averaged 26.85 and 27.7 bushels per acre (bu/A), respectively (USDA-NASS, 2019). Through the years 2010-2019, NC and VA yields increased to an average of 34.45 and 37.65 bu/A, respectively, an increase of 28 and 36 percent in comparison to yields from the 1990's. Despite increases, statewide yield averages for NC and VA are well behind the national average due to less productive soils than the Midwest where most soybean are grown and to lower yields due to late planting of a substantial number of double-crop soybean acres. Yield data and their positive trend for NC, VA, and the US can be found in Figure 1.

Soybean genetics and production practices as a whole have changed and improved over time leading to the increase in yield mentioned above. Row spacing is one practice that has been studied when aiming for high yielding production systems. Studies have found that 30-inch row spacing yield about 7 percent less than 7.5 or 15-inch row spacing (Hanna et al., 2008). Studies in North Carolina and Virginia suggested that seeding rate is another important practice to consider in relation to yield and maximizing return on investment (Stowe, 2019b., Parvej and Holshouser, 2017). These studies found that depending on the yield environment, planting date, and maturity group; seeding rates from 100,000-115,000 seeds per acre are sufficient for most situations unless planting occurs later in the season. However, Parvej and Holshouser (2017) found that under low yielding environments ranging from 20-40 bu/A, a seeding rate from 120,000 – 143,000 was needed. Timely planting is another critical production practice that has increased soybean yield and allowed for lower seeding rates. A regional analysis of the response of soybean yield to planting date found a rapid decline when planting after June 7th for the Upper South and May 27th for the Deep South with a yield decline of 1.1% and 1.2% per day (Egli and Cornelius, 2009). More recently Parvej et al. (2020) found in a 3-year, 5-state Mid-Atlantic project, that double-crop soybean yield declined quadratically with delayed planting in Pennsylvania, Delaware, and Virginia and linearly in Maryland (1.7% per day) and North Carolina (0.7% per day) when planted from late-May through mid-July. These agronomic practices along with improved varietal genetics and physiological changes has resulted in consistent yield increases of 0.42 bu/A per year and has undoubtedly altered nutrient utilization for the soybean plant (Naeve et al., 2018).

Macronutrients

With increasing soybean yields, nutrient management is an area that needs consideration. Yield is the primary factor determining soil nutrient removal (McGrath et al., 2013). Soybean in comparison with other crops, has a high nutrient uptake rate per bushel (IPNI, 2012). These figures vary regionally and figures can be slightly different depending on yield and growing conditions. Total aboveground uptake of 5.0 lb N, 1.0 lb P_2O_5 and 3.8 lb K_2O is required to produce a bushel of soybeans according to (Slaton et al., 2013). Additional figures found in Table 1 display nutrient uptake and removal for soybean in pounds per acre (IPNI, 2012). Macronutrients required for growth and development of soybean are mainly supplied to the soil through application of inorganic fertilizers or animal waste prior to planting. These nutrients are also supplied from soil nutrient reserves, biological nitrogen fixation by soybean roots, and decomposition of crop residue (McGrath et.al, 2013).

Nitrogen

Nitrogen (N) uptake for a 50 bu/A soybean crop is estimated at 277 lb/A (Stowe et. al., 2018). If effectively nodulated, soybean can fix a sufficient amount of N for optimum plant growth through a process called biological nitrogen fixation (Havlin et al., 2014). Proteins provided by NH_3 provide the framework for chloroplasts and mitochondria. In addition to the formation of proteins, N is a critical part of chlorophyll which converts light into energy needed for photosynthesis. Nitrogen is also utilized through mineralization of soil organic matter and N incorporated into plant tissue. Demand for seed N is greatest during R5 to R8 stages and N fixation decreases rapidly throughout this period (Fehr and Caviness, 1977). Due to a decrease in biological nitrogen fixation near seed development, additional N has been recommended by commercial agronomists for high yield management (Salvagiotti et al., 2009). Despite this claim, additional N fertilization results have been mixed. Welch et al. (1973) found that N fertilizer either decreased or had no effect on soybean seed yield. Similarly, Gutierrez-Boem et al. (2004) found that two rates of N applied at R3 and R5 stages had no effect on soybean seed yield. Moreira et al. (2017) also found yield differences of 3.14 bu/A and 3.85 bu/A from 4.5 and 9 lbs N per acre through soil applied or foliar applied N fertilizers at beginning pod growth stage but increases were not significant enough to offset costs. Experiments in Virginia (Freeborn et. al, 2001) found a lack of response from supplemental N suggesting that N supplied from soil organic matter mineralization and fixation was adequate for high yields. Most recently, a 1-year, multiple location study in North Carolina found a lack of response to 50 lbs/A of granular N at R1 (Vann, 2019).

Phosphorus

Phosphorus (P) is important for energy storage and transfer during plant development (Havlin et al., 2014). Like N, phosphorus is also important for root development (PPI, 2003). Phosphorus increases the plants N_2-fixation capacity and disease resistance is enhanced under adequate P availability. Phosphorus deficiency in soybean typically results in stunted plant growth. Phosphorus recommendations provided by soil testing is expected to resolve most yield limitations (Hardy, 2014). Tables 2, 3, and 4 display soil test levels and likely response to fertilization with P. Extensive field studies in Iowa using 3-18-18 foliar fertilizer reported both positive and negative yield responses with an average increase of 0.80 bu/A (Haq and Mallarino, 1998). Yield increases may have been attributed to additional N or K fertilization, however yield responses tended to occur with low early P uptake, sites with high soil CEC, and/or deficient rainfall in spring and midsummer. Studies with other macronutrient formulations reported that soybean response to foliar fertilization across all production conditions will seldom offset fertilization costs (Mallarino and Haq, 2001). 75 pounds of granular P at R1 found a lack of response in an NC study (Vann, 2019).

Potassium

Potassium (K) is necessary for synthesis and transport of photosynthates to plant reproductive and storage organs and subsequent conversion into carbohydrates, proteins, oils and other products (Havlin et al., 2014). Potassium is also critical for enzyme activation, osmotic pressure to draw water into the roots, photosynthesis, and energy relationships within the plant (PPI, 2003). The nutrient strengthens plant stalks and stems against invading organisms and lodging. Potassium is mobile in the plant, so deficiency symptoms usually appear first in the lower leaves progressing toward upper leaves (Havlin et al., 2014). Potassium deficiency is most frequent in coarse-texted, low CEC soils, soils with low exchangeable K, soils low in moisture and low temperatures, and low pH soils. Williams et. al. (2017) found an average yield loss of 45 percent due to K deficiency in soybean. The same study also found a significant amount of K in 6- to 12-inch and 12-24-inch deep samples, indicating its leaching potential in coarse-textured soils. Experiments were also conducted to determine if nutrient uptake from the soil was adequate to supply the needs of the plant during the seed-filling period of reproductive growth (Garcia and Hanaway, 1976). Their hypothesis was foliar fertilization is needed to avoid depleted levels of N, P, K, and S from the leaves. Their research found a significant increase from a formulation containing an NPKS ratio applied between R5 and R7. However, subsequent studies from a wide geographic region found variable, inconsistent, and occasionally reduced responses (Gray, 1977, Sesay and Shibles, 1980). Similarly, research on sites with low soil test K using a 0-0-19-13 foliar fertilizer at R1 did not increase yield at any of the four sites (Staton, 2019). A lack of response was also found from applying 75 lbs/A of granular K at R1 in North Carolina (Vann, 2019).

Secondary Nutrients

Sulfur, magnesium, and calcium are nutrients required in relatively large amount by most plants (Havlin et. al., 2014). Soil pH plays a critical role in soil availability of secondary nutrients (Reiter, 2020). Calcium deficiency of soybean is not typically observed in North Carolina except for instances of low pH (Stowe et al., 2018). Sulfur is another deficiency not often found in NC but is beginning to become a concern in other soybean producing regions (Kaiser and Kim, 2013).

Sulfur

Sulfur (S) is contained in every living cell and is a constituent of two of the 20 amino acids helping with protein formation (PPI, 2003). Sulfur also assists with development of enzymes and vitamins, promotes nodulation for N fixation, aids in seed production, and is necessary for chlorophyll formation. Sulfur is a vital part of ferredoxin, an Fe-S protein in chloroplasts, and has a significant role in NO_{2-} and SO_{4-2} reduction, and N assimilation by N_2-fixing soil bacteria (Havlin et al., 2014). The nutrient is supplied to the plant through soil organic matter mineralization, atmospheric deposition, and mostly through supplemental fertilization. The plant available form of sulfur, sulfate, is easily lost from the soil through leaching, but is accumulated in heavier (high clay content) subsoils; therefore, testing for sulfur in the topsoil is unpredictable. Sulfur deficiency can be found in coarse-textured soils low in organic matter. Much like N, P, and K, sulfur is required in large amounts by soybean so soil applied S fertilization is typically how deficiencies are handled. According to Bender et al. (2015), about 60% of the soybean plant's sulfur uptake occurs during reproductive growth with the majority being utilized during seed production. Foliar application of S did not increase yields in Michigan studies (Silva and Willson, 2018). Conversely, increases in yield were found using foliar applied S at 10 to 20 times higher than most foliar fertilizer products (Casteel, 2018). Most recently, a lack of response was found from 15 lbs/A of granular applied S at R1 in North Carolina (Vann, 2019).

Magnesium

Magnesium (Mg) is the central atom in the chlorophyll molecule, so it is involved with photosynthesis in the plant (Havlin et al., 2014). Magnesium also aids in phosphate metabolism, plant respiration, and the activation of many enzyme systems. Most NC soils have adequate levels of Mg due to dolomitic limestone being a common lime source for correcting soil pH (Hardy et al., 2014). Magnesium deficiencies can appear when there is an imbalance between Ca and Mg in low CEC soils. Liming soils primarily with calcitic aglime can cause this imbalance due to high soil test levels of Ca. Research on Mg foliar fertilization was not found.

Calcium

Calcium (Ca) is taken up by the plant as the Ca^{2+} cation. Calcium is important to N metabolism, protein formation by enhancing NO_3^- uptake, and providing regulation of cation uptake (Havlin et al., 2014). After uptake by the plant, calcium functions in several different ways: (1) stimulates root and leaf development, (2) forms compounds that are part of cell walls, strengthens plant structure, (3) helps reduce nitrate-N in the plant, (4) helps activate several plant enzyme systems, (5) helps balance organic acids in the plant (PPI, 2003). Lime, which contains calcium carbonate, provides the crop with adequate amounts of this nutrient (Hardy et al., 2014). Because of this, supplemental Ca is rarely needed and foliar fertilization studies evaluating Ca were not found.

Micronutrients

While required at much smaller levels, micronutrients perform specific biological functions, contribute to critical physiological processes, and are essential to soybean growth (Mallarino et al., 2017). Deficiencies of micronutrients in soils can significantly reduce crop yield, quality, and economic return (Marschner, 2002). Soil organic matter typically contains adequate micronutrient levels in plant available form. Nutrient uptake studies have found that the extremely low amounts of micronutrients accumulated throughout the growing season suggests that annual application of these nutrients is like not needed in most environments (Naeve et al., 2018). Studies evaluating soybean yield response to both broadcast applied and foliar applied micronutrient has led to mostly mixed results (Enderson et al., 2015, Freeborn et al., 2001, Mallarino et al., 2017, and Vann et al., 2019). Despite this research, there has been increased pressure for producers to apply micronutrients to soybean due to a perception that deficiencies have increased with increased yield (Sutradhar et. al, 2017).

Boron

Boron (B) is essential for growth and development and the primary function of B in the plant is cell wall structural integrity (Havlin et al., 2014). Boron is required in the plant for the function and formation of membranes, enzyme activation, and reproduction involving pollen tube growth and pollen germination. Boron is also essential for normal transport of water, nutrients, and photosynthetic sugars to rapidly developing growing tissues, such as root tips, leaves, buds, and storage tissues. Deficiencies can occur in areas of low rainfall when root activity is restricted, in alkaline or strongly acidic soils, sandy soils or soils low in organic matter. The boron ion (borate is like nitrate) is mobile in soil and can be leached from the root zone during heavy rainfalls, especially in coarse textured soils. Although B has been documented as one of the most commonly deficient micronutrients in agriculture, the need for B fertilization of soybean is unclear. Studies with 3 lb/A applied on a clay loam and fine sandy loam in Virginia found no effect on soybean yield over a 6-year study (Martens et al., 1974). Similarly, a 3-year study in Virginia (Freeborn J., et.al., 2001) found a lack of response to reproductive-stage B fertilizer applications to multiple cultivars, row spacing, and planting dates. Most recently, a 2-year, multiple environment study in NC found a 3.2 bu/A yield increase over unfertilized controls utilizing Smart B-Mo (Vann et. al., 2019). Nutrients contained in the product were likely deficient in the plant but plant tissues were not analyzed. Conversely, Enderson et al. (2015) found no increase of soybean yield from foliar applied B despite increased B concentration in grain at several sites. Schon and Blevins, (1990) found that foliar application of 0.01 lb/A was the optimal rate for increasing the number of pods per branch, but 0.02 lb/A promoted the highest seed yield per plant due to increase in seed size.

Manganese

Manganese (Mn) deficiency is a common occurrence in crops grown on coastal plain soils (Edwards, 1999). Manganese functions as a part of enzyme systems within the plant (PPI, 2003). One process it completes is activation of several important metabolic reactions and has a direct role in photosynthesis by aiding chlorophyll synthesis. The nutrient accelerates germination and maturity while increasing P and Ca availability. Manganese is immobile in the plant and deficiencies are associated with areas high in organic matter and in soils with neutral-to-alkaline pH. Deficiencies can also be associated with imbalances of Ca, Mg, and Fe. Environmental conditions such as cool, wet soils can be another factor causing Mn deficiency in the plant. Randall et al., (1975) indicated that applications of $MnSO_4$ and MnEDTA applied to the soil or foliage at early reproductive stages increased both leaf Mn concentrations and yield and Lang (2011) reported yield increases in 1 of a 3 year Mn study. Research in the Atlantic Coastal Plain region of the United States that included 38 trials found that the critical Mn concentration may range from 17 to 22 ppm for leaves at the R2 growth stage (Mascagni and Cox, 1985). A similar study (Edwards, 1999) saw a yield increase from foliar applications in Mn leaf concentration and yield when Mn soil and leaf indexes were low. Conversely, Enderson et al. (2015) found no increase of soybean yield from foliar applied Mn despite increased Mn concentration in grain at several sites.

Molybdenum

Molybdenum (Mo) is needed for synthesis and activity of the enzyme nitrate reductase and is needed for the reduction of NO_{3-} to NH_{+4} in the plant (PPI, 2003). Molybdenum is important for any leguminous plant as it helps with symbiotic N fixation by rhizobia bacteria in the root nodules. Another important function of molybdenum is conversion of inorganic P to the organic form for uptake and the absorption and translocation of Fe within plants. A deficiency of Mo in soybean can often lead to N deficiency due to a reduction of N fixation. Unlike most micronutrients, Mo becomes more available as pH increases, therefore deficiencies normally occur on course-textured, acidic soils low in organic matter. Low soil moisture can also lead to decreased plant uptake of Mo due to a reduction of mass flow to the root zone. As mentioned above, studies by Vann et. al. (2019) found a significant increase utilizing a foliar fertilizer containing B and Mo. Liming soils to the proper soil pH level can correct most Mo deficiencies (Mallarino et. al., 2017). Additional foliar fertilizer studies evaluating Mo were not found.

Zinc

Zinc (Zn) is necessary for synthesis of plant growth substances and enzyme systems and is essential for promoting certain metabolic reactions (Havlin et al., 2014). Chlorophyll and carbohydrate production is also reliant upon Zn. Another nutrient that is immobile within the plant, deficiencies can be found on new growth. Zinc deficiencies are more likely to occur in sands, sandy loams, loams, and organic soils than in silty or clayey soils (Schulte and Walsh, 1982). Other contributing factors that influence Zn deficiency include high soil pH, high soil P levels, low soil organic matter or conversely high organic matter soil can cause Zn to be fixed in the organic fraction, leaching, cold and wet soils, and lack of soil biological activity can all cause deficiencies. Soybean has a low to medium susceptibility to Zn deficiency, and is much less sensitive than corn, sorghum, or wheat (Mallarino et al., 2017). Field studies by Enderson et al. (2015) found no increase of soybean yield from foliar applied Zn despite increased Zn concentration in grain at several sites.

Iron

A main role of iron (Fe) in the plant is serving as a catalyst to chlorophyll formation (PPI, 2003). It also acts as an oxygen carrier in the nodules of legume roots and helps with formation of certain respiratory enzyme systems. Iron like many other micronutrients is immobile within the plant. Deficiencies in the plant can likely be attributed to factors such as excessive P in the soil, combinations of high pH, wet, cold soils, high bicarbonate levels, plant genetic differences, or low soil organic matter levels (Havlin et al., 2014). Foliar application of chelated Fe fertilizer sources has been inconsistent. It has been successful in reducing signs of chlorosis in soybean at some locations (Goos and Johnson, 2000), increasing yield in some cases (Penas et al., 1990), and has had no effect at other locations in soybean (Lingenfelser et al., 2005). Field studies in NC found early reproductive stage applications increased yields by 2.6 bu/A over the unfertilized check utilizing a foliar product containing Fe (Vann et al., 2019).

Cobalt

Cobalt (Co) is essential for microorganisms such as rhizobia that fix molecular N_2 (Havlin et al., 2014). Cobalt is a component of several soil minerals and soil organic matter. Plants grown on acid, highly leached, and sandy soils can benefit from Co. Deficiencies can also be found on highly calcareous soils and some peaty soils. Additional foliar fertilizer studies evaluating Co were not found.

Copper

Copper (Cu) is a component of several enzymes that play roles in photosynthesis, respiration, lignin formation in cell walls, and carbohydrate and lipid metabolism (Havlin et al., 2014). Copper exists in various soil minerals and is complexed in soil organic matter. Soybean is considered among the least susceptible crops to Cu deficiency (Mallarino et al., 2017). Still, deficiencies could occur in organic, sandy, and/or calcareous soils that are cool and wet. Studies by Enderson et al. (2015) found no response to foliar applied Cu and in some cases, yields decreased.

Aluminum

Aluminum (Al) is not an essential plant nutrient, however Al can be toxic to plants when soils contain large amounts of the element (Havlin et al., 2014). Aluminum toxicity usually occurs when soil pH is less than 5.5, but depends on the crop and variety. Acidic soils can also severely inhibit root elongation, restrict root growth, and restrict nutrient availability. Liming soils to suitable pH ranges lowers exchangeable Al, and Al solution in the soil decreases with increasing pH.

Research on foliar fertilization has been inconclusive in NC and VA (Vann et al., 2019; Freeborn et al., 2001) and throughout soybean producing areas as a whole (Enderson et. al., 2015; Mallarino et. al., 2017). Low commodity prices as well as increasing input costs and land prices increases the need for research on foliar fertilizers. Therefore, the main objectives of this research were (1) to evaluate soybean tissue concentration and yield response to foliar fertilization and (2) to evaluate foliar fertilization profitability.

Materials and Methods

Site Characteristics

Experiments were conducted during the 2019 growing season at four different locations in two different states. Three trials (Boonville, Dunn, and Shawboro) were conducted in NC on grower owned sites. The fourth location (Suffolk) was conducted at Virginia Tech's Tidewater Agricultural Research and Extension Center in Suffolk, VA. A soil description for each location can be found in Table 5. Soil samples were collected prior to planting at an eight-inch depth from each trial location. Properties measured included texture, phosphorus, potassium, calcium, magnesium, sulfur, zinc, manganese, iron, copper, boron, organic matter, cation exchange capacity and soil pH. Mehlich III extraction utilizing inductively coupled plasma (ICP) was used for NC locations to analyze P, K, Ca, Mg, S, Zn, Mg, Fe, Cu, and B. Mehlich I was utilized to analyze Suffolk soil sample properties; P, K, Ca, Mg, Zn, Mn, Fe, and B. A Bouyoucos hydrometer was used to take measurements of the soil solution to analyze soil texture. The percent sand, silt, and clay in the soil suspension was calculated, and the USDA textural triangle was used to determine the soil type. Soil sample test results from each location can be found in Table 6.

Experimental Design

Experimental design was a randomized complete block with six replications. Six treatments that included combinations of macro, secondary, and micronutrients were applied to soybean to evaluate response to in-season foliar fertilizer formulations. An untreated control was also included as a comparison. Products evaluated and their application rate can be found in Table 7. Treatments were applied at soybean development stage R3 to align with commonly used fungicide and/or insecticide application timings using a CO_2 backpack sprayer. The R3-stage in soybean is determined as the beginning pod stage where soybean pods are measured at three sixteenth of an inch long at one of the four uppermost nodes of the main stem (Pederson, 2004). Table 8 displays pounds of nutrient per acre for each product at the applied rate. Testing at multiple locations allowed for information generation from varying yield environments while utilizing multiple production practices. Production practice information and GPS coordinates for each location can be found in Table 9.

Tissue Testing and Analysis

To evaluate in-season nutrient status, plant tissue samples were collected at two different timings (Table 10). The first plant tissue sample collection was within twenty-four hours prior to foliar application. The second timing for plant tissue collection was two weeks after application. At both sampling intervals, twenty uppermost fully developed trifoliolate leaves were randomly collected from each plot with the petioles removed. Trifoliolates were placed in paper bags and were dried at 140 degrees for 72 hours. Total nitrogen concentration was determined by oxygen combustion gas chromatography with an elemental analyzer (NA1500s2; CE Elantech Instruments; Lakewood, NJ) on 5-7 mg aliquot of the dried sample (NCDA, 2015). The remaining nutrients analyzed consisted of: P, K, Ca, S, Mg, B, Cu, Fe, Mn, and Zn. Tissue concentration for these nutrients was determined with inductively coupled plasma-optical emission spectrometry (NCDA, 2015). Plant tissue nutrient concentrations before and after treatments and the percent change of nutrient content in parts per million can be found in Tables 11-13. Percent change was calculated by finding nutrient concentration difference between the first and second plant tissue samples and then dividing by the first sample date concentration.

Soybean Yield

Yield was determined by harvesting soybean from 40 feet of the four center rows for the NC locations and 17 feet of the four center rows for the Virginia location. A plot combine was used for harvest at all locations. Moisture was adjusted to thirteen percent. Soybean yield information can be located at Table 14.

Statistical Analysis

Tissue nutrient concentration prior to and after treatments, percent change, and soybean yield were subjected to an analysis of variance using PROC GLM in SAS 9.3 (SAS Institute, 2019). Means were separated using Fisher's protected LSD with P=0.10.

Results and Discussion

Soybean Yield Response to Foliar Fertilization

There were no yield increases ($P \leq 0.10$) from any treatment at any site (Table 14). When evaluating the compiled soil test values prior to planting (Table 6) and soil test sufficiency ranges (Tables 2, 3, and 4) for NC and VA, a response to additional P or K fertilization was not expected because both P and K soil test levels were considered to be in the "medium" or "high" range according to NC and VA soil test recommendations. While the soil sample report (Table 6) gives values for S, Zn, Mn, Fe, Cu, and B; gauging a response to additional fertilization would be difficult unless paired with plant tissue analysis.

According to interpretive plant tissue sufficiency ranges (Tables 15, 16, and 17), responses to additional fertilizer to certain nutrients were expected at R3-stage, but was dependent on sufficiency ranges determined by each laboratory. Prior to treatments being made, P concentration at the Boonville location averaged 26 ppm. Table 15 indicated that sufficient P levels range from 30-60 ppm, but Table 16 indicated that P levels ranging from 25-34 ppm gives only a "small probability of response", and Table 17 indicated that 26-50 ppm P levels are in the "sufficient" range. Potassium concentration prior to treatment averaged 129, 129, 137, and 200 ppm at the Boonville, Dunn, Shawboro, and Suffolk locations, respectively. Potassium sufficiency ranges according to Table 15 is 150-225 ppm, Table 16 indicated a likely response to K fertilization when tissue levels are less than 170 ppm, and Table 17 indicated levels between 126-170 ppm as "low". However, Parvej et al. (2016) found that regardless of soybean cultivar or annual-K rate, K concentration for the uppermost, recently-mature trifoliolate leaves increases linearly to a plateau from the mid-vegetative (V5-V7) to the early reproductive stages (R1-R3) and then declines linearly throughout reproductive growth. This decline as soybean progresses toward maturity was attributed to increased dry matter production and translocation of K to the developing seeds. Furthermore, uptake of K is high for soybean (Table 1) and nutrient uptake is most rapid between R3 and R4 growth stages (Bender et al., 2015). The decline in K beginning at R3 and the rapid uptake of K at this stage could explain the lack of yield response to this nutrient even though tissue concentrations were borderline low. Sulfur concentration at the Boonville location averaged 23 ppm prior to treatments. Table 15 indicated that S sufficiency ranges fall between 25-60 ppm, Table 16 indicated a "likely response" when S levels are less than 25 ppm, and Table 17 indicated low S levels ranging between 21-35 ppm. The remaining nutrient concentrations at all locations measured in either the "sufficient range" or "high" ranges prior to treatment. Manganese deficiencies are most frequent in VA and K deficiency is the most prominent nutrient deficiency in plant tissue samples analyzed by the NCDA (Maguire and Heckendorn, 2019, Stowe, 2019a.), but products containing that nutrient did increase yield nor were deficiency symptoms observed.

Soybean Tissue Concentration Response to Foliar Fertilization

Nutrient uptake is most rapid between R3 to R4, peaking at R4 (Bender et al., 2015). Uptake of K and Fe primarily occurs during late vegetative and early reproductive growth while uptake of N, P, Ca, Mg, S, Zn, Mn, B, and Cu is distributed evenly throughout the entire growing season. Peak N uptake occurs between R4-R5 with the greatest uptake rate totaling 4 lbs N/A/day (Naeve et al., 2018). Peak P uptake occurs between R3-R4 with a peak rate of 1.2 lbs/P_2O_5/A/day. Peak K uptake occurs shortly after R2 ranging from 3.5-5.2 lbs K_2O/A/day. Sulfur uptake peaks at approximately 0.3 lbs S/A/day depending on yield level shortly after R3. Calcium and magnesium uptake peaks at R3 with uptake rates of 0.6 and 1.8 lbs/A/day respectively. Lastly micronutrient uptake in general peaks near R3 with less than 0.01 lbs/A/day. Listed below are the products utilized in this study and their effect on plant tissue nutrient concentration when applied at R3. It is important to remember the rapid uptake and remobilization of these nutrients from plant tissue to seed for development during these reproductive stages. Nutrient concentration percent change in Table 13 displays the effect of this nutrient remobilization as many of the nutrients have a negative percent change. It is also important to consider the relatively small amount of nutrient applied in these products in comparison to the pounds of nutrient required by soybean (Table 1). Nutrients applied in lb/A and rate applied can be found for each product below in Tables 7 and 8.

FertiRain

FertiRain contained a mixture of N, P, K, S, Mn, Zn, and Fe. Of these nutrients, the product significantly raised Fe plant tissue levels two weeks after treatment by 10.2% and 5.8% in comparison with the control at the Boonville and Dunn locations, respectively. Prior to treatments, P tissue concentration was sufficient at three of four locations with low concentration levels being found at the Boonville location, K tissue concentration was low at Boonville, Dunn, and Shawboro but was sufficient in Suffolk, and S tissue concentration was low at the Boonville location prior to treatment but was sufficient at all other locations. All other nutrient concentrations were sufficient prior to treatment. Other nutrients that were contained in the product mixture did not have an effect on tissue concentration.

Sure-K

Sure-K contained a mixture of N, P, and K. Of these nutrients, the product led to a 7.0% and 7.4% reduction of N and P loss in plant tissue concentration in comparison with the control at the Boonville location two weeks after treatments. Potassium tissue concentration was unaffected at all four locations and N and P were unaffected at the three remaining locations. Prior to treatments, N tissue concentration was sufficient at all four locations, P tissue concentration was sufficient at three of four locations with low concentration levels being found at the Boonville location, and K tissue concentration was low at Boonville, Dunn, and Shawboro but was sufficient in Suffolk.

Smart B-Mo

Smart B-Mo contained a mixture of B and Mo. Of these nutrients, the product significantly raised B plant tissue concentration two weeks after treatment in comparison with the control at three of the four locations. B plant tissue concentration in were raised 42.6%, 39.2%, and 41.6% at the Boonville, Shawboro, and Suffolk locations, respectively. Prior to treatments, B plant tissue concentration was sufficient at all locations. Molybdenum was contained in the product mixture; however, Mo was not one of the nutrients analyzed by the plant tissue test.

Smart Quarto-Plus

Smart Quatro-Plus contained a mixture of S, Mn, Mo, Zn, and B. Of these nutrients, the product significantly raised Zn plant tissue concentration two weeks after treatment in comparison with the control by 27.3% at the Suffolk location. Sulfur tissue concentration was low at the Boonville location prior to treatment but was sufficient at all other locations. Prior to treatments, Mn, Zn, and B tissue concentration was sufficient at all locations. Molybdenum was also contained in the product mixture; however, Mo was not one of the nutrients analyzed by the plant tissue test. All other nutrients contained in the mixture had no effect on tissue concentration.

Maximum N-Pact K

Maximum N-Pact K contained a mixture of N and K. Neither N nor K had an effect on tissue concentration at any of the four locations two weeks after treatment in comparison with the control. Prior to treatments, N tissue concentration was sufficient at all locations while K concentration was low at Boonville, Dunn, and Shawboro but was sufficient at Suffolk.

HarvestMore UreaMate

HarvestMore UreaMate contained a mixture of N, P, K, Ca, Mg, Mn, Mo, Zn, B, Co, and Cu. Of these nutrients, the product significantly raised Cu plant tissue concentration two weeks after treatment in comparison with the control at three of the four locations. Copper tissue concentration was raised 13.3% at Dunn, 13.2% at Shawboro, and 13.4% at Suffolk. There was also a 16.7% and 9.7% reduction of Cu and K loss in the tissue at the Boonville location in comparison with the control. Zinc plant tissue concentration was significantly increased by 13.7% at the Suffolk location in comparison with the control. Prior to treatments, P tissue concentration was low in Boonville and K tissue concentration was low in Boonville, Dunn, and Shawboro. All other nutrient concentrations were sufficient prior to treatment. Other nutrients that were contained in the product mixture did not have an effect on tissue concentration.

Profitability of Foliar Fertilizer Usage

To calculate return or loss from utilizing foliar fertilizers, a group of local industry professionals were surveyed to get an average cost per acre for each product (Table 18). These costs only reflect the cost per acre of the product at the rate applied in the study. It was assumed that the producer would make a fungicide or insecticide application so cost per acre to spray was not included. No differences in yield from foliar fertilizer use led to a profitability reduction for each product in this study. Loss of return per acre for the cost of the product ranged from $3.83/A to $22.11/A (Table 18). With low commodity prices, all input costs have to be considered. Fungicide or insecticide applications depending on disease or insect prevalence is a common input during reproductive growth of soybean. As stated earlier, the R3 application timing of treatments for this study was chosen due to the likelihood of producer’s tank mixing a foliar fertilizer with a fungicide or insecticide application.

Conclusion

Foliar fertilizer products that were utilized in this study did not increase soybean yield at any of the four locations when applied at R3. Plant tissue concentrations for N, P, K, B, Cu, Fe, and Zn were increased in some instances by treatments containing those nutrients. Responses might have been expected due to relatively low tissue concentration of P, K, and S at select locations, but products containing those nutrients did not increase yield. Greatest plant tissue concentration response was increased B concentration in 3 of 4 locations from application of Smart B-Mo. As a whole, pre-plant lime and fertility at all locations followed by North Carolina and Virginia Cooperative Extension recommendations was sufficient for soybean growth and did not limit soybean yield. With a lack of soybean yield response to foliar fertilizers, additional foliar feeding did not offset application costs. Although these limited results indicate no yield advantage to including foliar fertilizer to R3-stage soybean applications, further research may be necessary to fully determine if foliar fertilization of soybean is beneficial. Additional studies should be conducted over varying environments to determine potential benefits of applying foliar fertilizers with corresponding application timing and rates.

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Figures

Figure 1: 30-year soybean yield trend for U.S., N.C., and V.A.

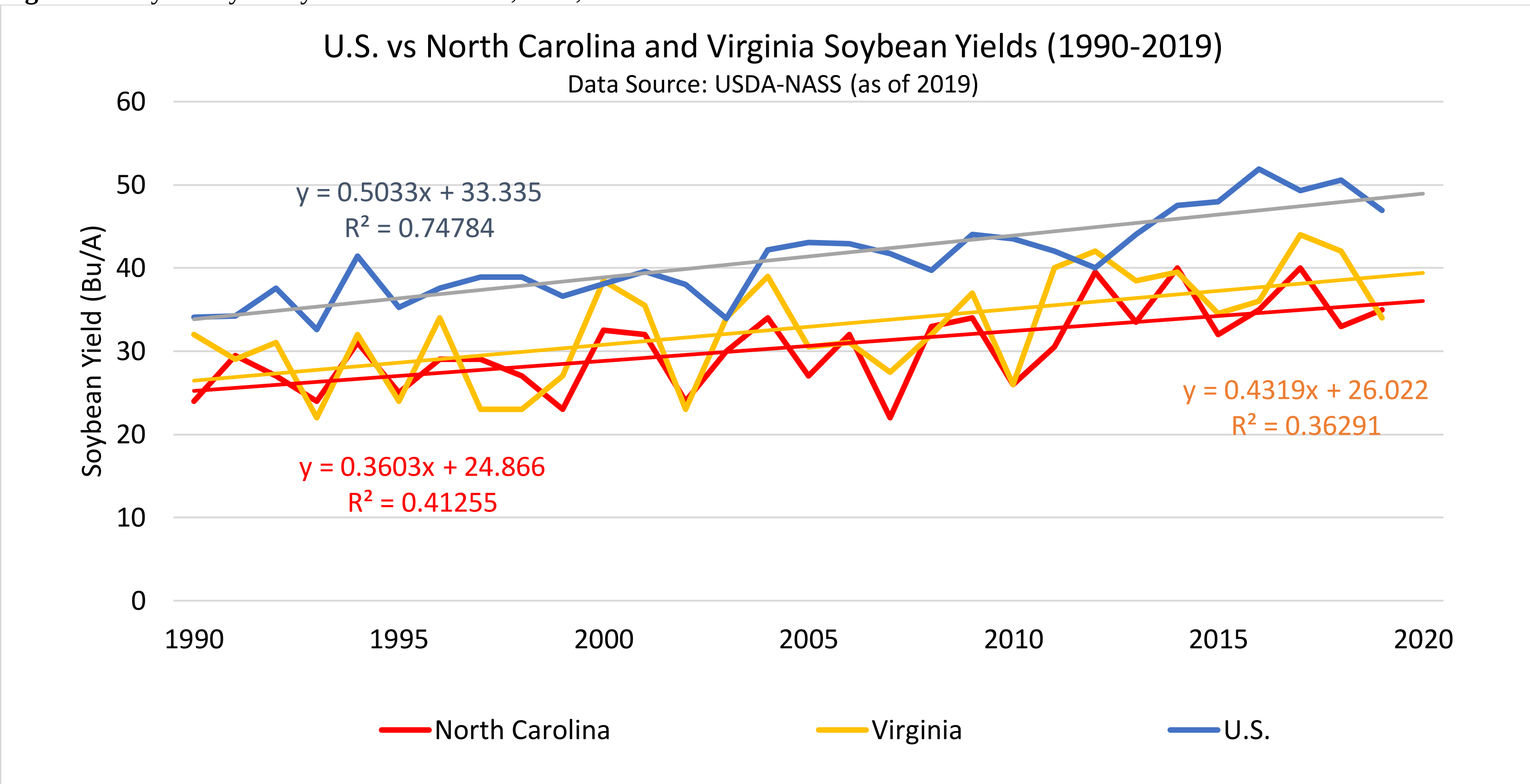
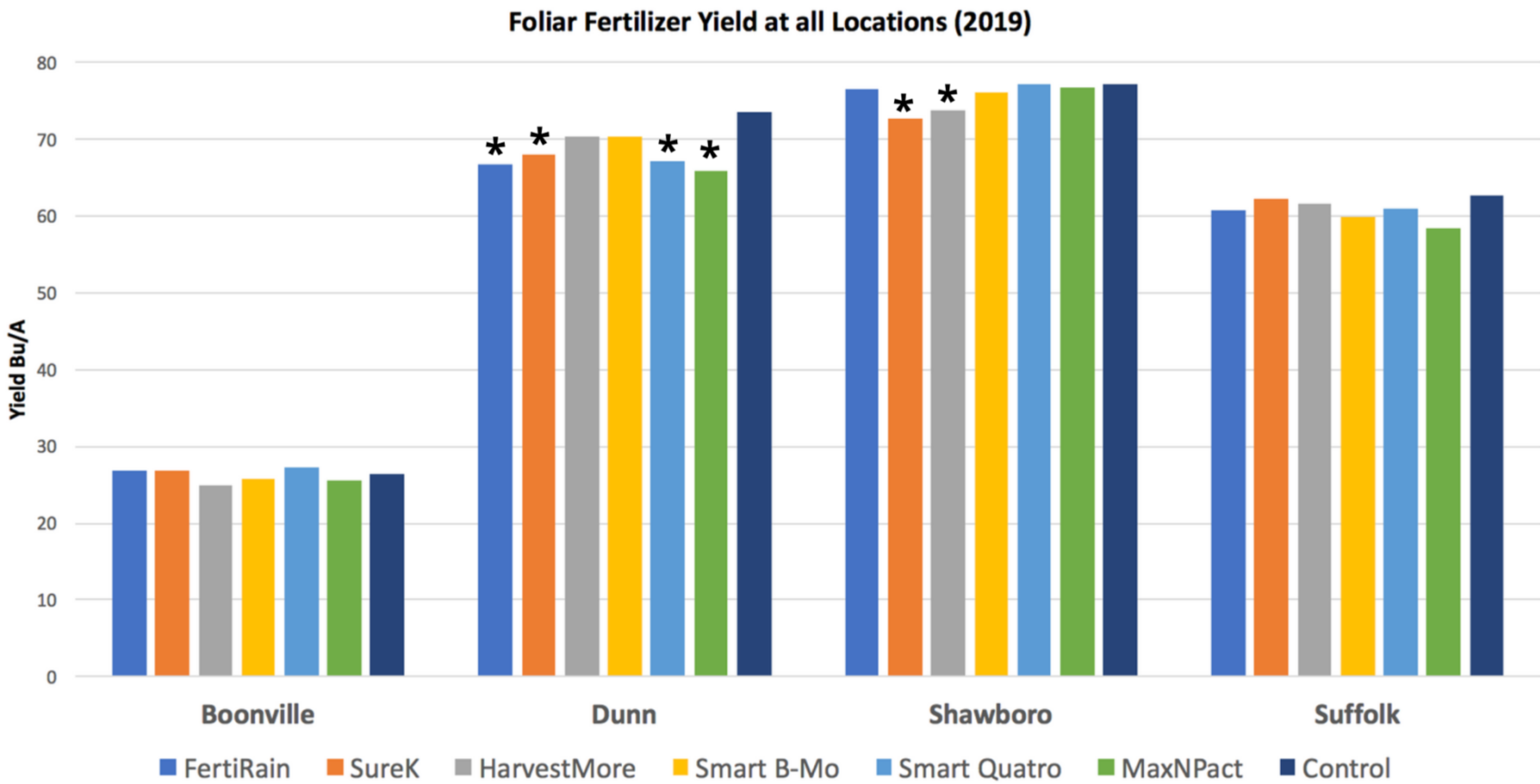


Figure 2: Foliar fertilizer yield at all locations (no significant yield increases by any treatment at any location with *P*=0.10).



*Indicates significant yield decreases (*P*=0.10).

Tables

Table 1: Total nutrient uptake and nutrient removal in pounds per acre.

	N	P_2O_5	K_2O	Mg	S
			lbs/A		
Grain	3.8	0.84	1.3	0.21	0.18
Stover	1.1	0.24	1.0	0.22	0.17
Total	4.9	1.08	2.3	0.43	0.35

(International Plant Nutrition Institute: Estimates of Nutrient Uptake and Removal, 2012.)

Table 2: NCDA Mehlich III soil test calibration in ppm.

Element	Very low	Low	Medium	High	Very high
P	<13*	13-30*	31-60	61-120	>120
K	<21*	21-49*	50-99	100-195	>195
Mn	<1.7*	1.7-4.0*	4.1-8.0	8.1-16.0	>16
Zn	<0.5*	0.5-1.0*	1.1-2.0	2.1-4.0	>4.0
Cu	<0.3*	0.3-0.5*	0.6-1.0	1.1-2.0	>2.0

*Expected crop response to fertilizer when soil levels are low to very low.

Table 3: Virginia Tech Mehlich I soil test calibration in ppm.

Element	L-	L	L+	M-	M	M+	H-	H	H+	VH
P	0-2	2-4	5-6	6-10	11-15	16-18	18-28	28-43	43-55	55+
K	0-8	8-28	28-38	38-50	51-75	76-88	88-105	106-140	141-155	155+
Ca	0-120	121-240	241-360	361-480	481-600	601-720	721-840	841-960	961-1080	1200+
Mg	0-12	13-24	25-36	37-48	49-60	61-72	73-84	85-96	97-108	109+

Maguire, R. O., and Heckendorn, S. E. (2019). Soil Test Recommendations for Virginia.

Table 4: Water's Lab Mehlich III soil extraction parameters.

Element	Low	Moderate	Adequate	High	Very High
P	<40	41-100	101-150	151-200	201+
K	<125	125-225	226-325	326-425	426+
Mg	<100	101-150	151-250	251-300	301+
Ca	<600	601-1000	1001-1400	1401-1800	1801+
S	<25	26-50	51-75	76-100	101+
B	<1.0	1.0-1.5	1.6-2.0	2.1-2.5	2.6+

Zn	<4.0	4.0-6.0	6.1-10.0	10.1-14.0	14.0+
Mn	<30	31-60	61-200	201-400	401+
Fe	<50	51-100	100-200	201-400	401+
Cu	<1.50	1.6-3.0	3.1-6.0	6.1-12.0	12.1+

(Waters Agricultural Laboratories, INC., 2020).

Table 5: Soil classification and characteristics for all locations.

Soil classification			**Soil characterization**					
Site	**Series**	**Type**	**OM**	**CEC**	**pH**	**Clay**	**Silt**	**Sand**
			%			%	%	%
Boonville	Nathalie	Sandy loam	1.8	3.6	5.5	16	19	65
Dunn	Goldsboro	Loamy sand	0.8	3.6	6.0	7	14	79
Shawboro	Roanoke	Silt loam	1.9	7.4	5.7	18	52	30
Suffolk	Dragston	Loamy fine sand	1.1	3.8	6.3	-	-	-

*NC locations were analyzed at A&L Great Lakes Laboratories in Fort Wayne, Indiana
*Suffolk location sample was analyzed by Dr. Mark Reiter at the Eastern Shore Agricultural Research and Extension Center.

Table 6: Soil sample report (0-8” depth) prior to planting for all locations in ppm.

Site	**P**	**K**	**Mg**	**Ca**	**Na**	**S**	**Zn**	**Mn**	**Fe**	**Cu**	**B**
Boonville	73	67	52	342	12	7	6	18	16	0.9	0.2
Dunn	121	70	49	350	17	7	5	17	17	3	0.3
Shawboro	41	67	198	650	22	14	2	10	69	0.9	0.4
Suffolk	41	132	117	988	-	-	2	12	8	-	0.3

*Boonville, Dunn, and Shawboro soil test values calculated with Mehlich III extracting solution.
*Suffolk soil test values calculated with Mehlich I extracting solution.

Table 7: List of foliar product names, brands, and application rate.

Treatment	**Treatment Name**	**Company**	**Application Rate**
1	FertiRain	AgroLiquid	3 gal/A
2	Sure-K	AgroLiquid	3 gal/A
3	Smart B-Mo	Brandt	1 pt/A
4	Smart Quatro Plus	Brandt	1 qt/A
5	Maximum N-Pact K	Nutrien	1.5 gal/A
6	HarvestMore UreaMate	Stoller	2.5 lbs/A
7	Untreated Control	-	-

Table 8: Nutrients applied for each treatment in lb/A.

Treatment Name	N	P	K	S	Mn	Mo	Zn	B	Fe	Other
FertiRain	3.5	0.9	0.9	0.5	0.02	-	0.03	-	0.03	-
Sure-K	0.6	0.3	1.7	-	-	-	-	-	-	-
Smart B-Mo	-	-	-	-	-	0.006	-	0.07	-	-
Smart Quatro Plus	-	-	-	0.04	0.08	0.003	0.08	0.06	-	-
Maximum N-Pact K	1.9	-	1.9	-	-	-	-	-	-	-
HarvestMore UreaMate	0.75	1.5	4.05	-	0.075	0.001	0.075	0.02	-	*
Untreated Control	-	-	-	-	-	-	-	-	-	-

*HarvestMore UreaMate additional applied nutrients in lbs/A: Ca 0.6, Mg 0.225, Co 0.001, Cu 0.04.

Table 9: Production practices and GPS coordinates for all locations.

	Boonville	Dunn	Shawboro	Suffolk
Variety	AG64X8	AG56X8	AG54X9	AG56X8
Previous crop	Soybean	Corn	Corn	Corn, Wheat
Tillage	No-till	Conventional	Conventional	No-till
Plot Length	40’	40’	40’	17’
Plot Width	20’	10’	8.75’	6’
Row Spacing	30”	15”	15”	15”
Seeding Rate	120,000	120,000	120,000	210,000
Planting	5/21/2019	5/22/2019	5/9/2019	6/26/2019
Harvest	11/7/2019	10/24/2019	10/25/2019	11/25/2019
GPS Coordinates	36.20492 N, -80.736938 W	35.233337 N, -78.437251 W	36.388502 N, -76.123188 W	36.682471 N, -76.766250 W

Table 10: Tissue sampling and treatment applications dates for all locations.

	Boonville	Dunn	Shawboro	Suffolk
1st Tissue	9/4/2019	8/26/2019	8/6/2019	9/3/2019
Treatment	9/4/2019	8/26/2019	8/6/2019	9/4/2019
2nd Tissue	9/18/2019	9/9/2019	8/20/2019	9/18/2019

Table 11: Average plant tissue nutrient concentration in upper fully mature trifoliate prior to treatment in ppm at all locations.

Boonville

Product	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Al**
FertiRain	463ab	26a	132a	167a	34a	23a	79a	53a	98ab	8.8a	52ab	9.1ab
SureK	452ab	26a	128a	174a	35a	22a	78a	56a	88cd	8.8a	54a	11.1a
HarvestMore	462ab	26a	127a	163a	34a	23a	77a	51a	87d	8.8a	54a	9.0ab
SmartBMo	455ab	26a	128a	168a	35a	22a	75a	50a	89bcd	8.7a	51b	8.7ab
SmartQuatro	447b	26a	131a	166a	35a	22a	76a	58a	104a	9.0a	52ab	9.9ab
MaxNPact	469ab	26a	126a	165a	33a	23a	79a	54a	97abc	8.9a	53ab	10.7ab
Control	471a	27a	133a	175a	35a	23a	80a	57a	96abcd	9.2a	54ab	8.5b
LSD (0.10)	23.61	1.72	10.65	15.50	2.95	1.34	5.39	8.01	9.49	0.62	3.12	2.44

Dunn

Product	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Al**
FertiRain	497b	32ab	130abc	181ab	32a	26ab	82ab	69ab	74ab	7.9c	46a	6.7ab
SureK	521a	32a	132ab	177ab	31a	26ab	81ab	63b	76ab	8.2ab	45a	7.2ab
HarvestMore	517a	31ab	123c	183a	32a	26ab	81ab	68ab	73ab	8.0abc	47a	6.7ab
SmartBMo	512ab	31ab	129abc	180ab	32a	25ab	80ab	61b	69b	7.9bc	46a	6.2b
SmartQuatro	523a	31b	125bc	171b	32a	25b	79b	61b	70b	7.8c	44a	6.7ab
MaxNPact	516a	32a	135a	176ab	31a	26a	80ab	74a	84a	8.2ab	46a	6.7ab
Control	523a	31ab	126bc	176ab	31a	26ab	82a	66ab	75ab	8.3a	45a	8.4a
LSD (0.10)	497b	32ab	130abc	181ab	32a	26ab	82ab	69ab	74ab	7.9c	46a	6.7ab

Table 11: Continued

Shawboro												
Product	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Al**
FertiRain	514a	31ab	140a	164a	46a	28a	137bc	116a	93a	11.7a	23b	5.5a
SureK	526a	32a	143a	150a	44a	28a	133bc	97b	86a	11.2a	23ab	5.8a
HarvestMore	528a	32a	141a	157a	46a	29a	172a	114a	91a	11.6a	23b	6.3a
SmartBMo	535a	31a	136a	165a	46a	29a	152ab	118a	95a	11.8a	24a	5.9a
SmartQuatro	529a	31a	134a	161a	47a	29a	131bc	111ab	93a	11.8a	23b	6.2a
MaxNPact	526a	31ab	138a	156a	44a	28a	122c	112ab	91a	11.4a	23b	5.2a
Control	524a	30b	129a	156a	46a	28a	132bc	104ab	91a	12.1a	22b	6.1a
LSD (0.10)	25.70	1.23	18.00	21.59	4.37	1.84	28.12	16.74	11.91	1.15	1.05	1.40

Suffolk												
Product	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Al**
FertiRain	601b	44a	196c	87a	35b	30a	106a	31a	40a	9.0ab	31a	8.9a
SureK	599b	47a	201abc	84a	36ab	29b	98b	31a	39a	8.2b	29a	6.6a
HarvestMore	627a	45a	198bc	89a	35b	29ab	102ab	32a	38a	8.4ab	31a	8.8a
SmartBMo	613ab	48a	204ab	84a	38a	29ab	101ab	36a	41a	8.3ab	30a	7.6a
SmartQuatro	622ab	46a	201abc	85a	36b	30ab	104a	29a	39a	9.2a	31a	6.8a
MaxNPact	626a	47a	197bc	83a	36ab	29ab	103ab	31a	40a	8.7ab	31a	7.3a
Control	609ab	47a	205a	85a	36ab	29ab	102ab	30a	39a	8.7ab	31a	9.5a
LSD (0.10)	24.65	4.27	6.61	5.62	2.26	1.40	5.32	7.88	3.54	0.89	3.19	4.40

*[a]Means followed by the same letters are not significantly different using Fisher's Protected LSD at P=0.10.

Table 12: Average plant tissue nutrient concentration in uppermost fully mature trifoliate two weeks after treatment in ppm at all locations.

Boonville

Product	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B	Al
FertiRain	352abc	22ab	113ab	232abc	35a	22a	91a	57a	88a	6.6b	57bc	29.2a
SureK	359ab	22a	111b	240a	37a	22a	86b	64a	96a	6.7b	58bc	28.9a
HarvestMore	344bc	21ab	116ab	227c	35a	21a	81c	57a	83a	7.6a	56c	27.1a
SmartBMo	360a	22a	113ab	240ab	37a	22a	84bc	56a	90a	6.6b	77a	27.4a
SmartQuatro	345bc	21ab	120a	228bc	35a	21a	82bc	63a	96a	6.1c	61b	27.0a
MaxNPact	340c	21b	115ab	229abc	36a	22a	81c	60a	87a	6.1c	57bc	28.4a
Control	345bc	22ab	110b	234abc	36a	21a	85b	60a	87a	6.5bc	58bc	29.0a
LSD (0.10)	14.62	0.93	9.40	12.28	4.65	1.06	3.65	11.08	15.47	0.48	4.23	3.50

Dunn

Product	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B	Al
FertiRain	446ab	29	120	206	25	25	89a	71a	73ab	7.6a	41ab	10.2a
SureK	447ab	29	123	205	25	26	87a	74a	82a	8.3a	41ab	9.7a
HarvestMore	436b	29	115	218	26	25	69b	58a	58b	7.1a	34b	6.4b
SmartBMo	449a	30	116	210	25	26	85a	67a	71ab	7.2a	44a	8.5ab
SmartQuatro	449ab	29	118	209	26	26	90a	76a	81a	7.3a	38ab	8.1ab
MaxNPact	451a	30	121	205	24	26	81ab	77a	78ab	7.5a	39ab	7.1b
Control	448ab	29	121	212	26	26	85a	72a	70ab	7.8a	40ab	8.1ab
LSD (0.10)	13.19	1.02	5.41	11.06	1.70	1.45	13.04	19.91	20.89	1.58	6.99	2.43

Table 12: Continued

Shawboro												
Product	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Al**
FertiRain	486ab	29ab	106a	203b	44ab	28a	113ab	122ab	107a	11.2b	21b	8.6a
SureK	493ab	29b	102abc	220a	46a	27a	112ab	122ab	101b	10.5c	21b	6.3abc
HarvestMore	496ab	29ab	102abc	212ab	44ab	28a	120ab	133a	108a	11.8a	21b	7.8ab
SmartBMo	501a	30a	105ab	213ab	43b	28a	132a	131ab	103ab	10.9bc	32a	4.7c
SmartQuatro	483b	28b	99c	210ab	46ab	26b	105b	124ab	106a	10.6c	20b	5.0c
MaxNPact	488ab	29ab	104abc	213ab	44ab	27ab	107b	134a	105ab	10.8bc	20b	5.7bc
Control	488ab	29ab	101bc	220a	47a	27a	103b	116b	101b	10.6c	21b	5.0bc
LSD (0.10)	17.48	1.06	5.38	14.92	3.34	0.82	20.01	17.01	5.16	0.43	1.04	2.72

Suffolk												
Product	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Al**
FertiRain	541a	33ab	134a	133a	28a	27ab	110ab	40a	43ab	9.1ab	21bcd	14.5ab
SureK	534a	34a	135a	133a	29a	27a	104d	37a	37b	8.2bc	20d	12.0b
HarvestMore	532a	34a	131a	139a	29a	27a	109abc	41a	41ab	9.2a	22bcd	13.4b
SmartBMo	534a	32b	131a	130a	28a	26b	102d	38a	36b	7.8c	32a	17.1a
SmartQuatro	540a	34a	133a	139a	29a	27a	113a	43a	47a	8.3abc	22bc	13.3b
MaxNPact	534a	33a	137a	133a	28a	27ab	107dbc	39a	40ab	8.6abc	22b	14.2ab
Control	539a	33ab	135a	135a	28a	27ab	104dc	37a	36b	8.3bc	20cd	13.4b
LSD (0.10)	26.55	1.65	7.51	12.68	2.58	1.22	5.28	15.90	7.40	0.89	1.91	3.18

*[a]Means followed by the same letters are not significantly different using Fisher's Protected LSD at *P*=0.10.

Table 13: Average % change of plant tissue nutrient concentration in uppermost fully mature trifoliate after treatment at all locations.

Boonville

Product	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B	Al
FertiRain	-23.9bcd	-17.8ab	-14.3ab	40.9a	5.1a	-4.9ab	16.4a	6.9a	-9.7b	-24.6b	10.2bc	231.8ab
SureK	-20.4a	-12.8a	-13.4ab	38.4a	6.1a	-2.7ab	10.3ab	19.2a	9.1a	-23.8b	7.4bc	189.9ab
HarvestMore	-25.4bcd	-16.1ab	-7.2a	39.6a	1.6a	-6.5b	4.7bc	11.5a	-2.9ab	-13.4a	2.5c	215.5ab
SmartBMo	-20.6ab	-12.8a	-10.7ab	42.9a	8.3a	1.4a	12.2ab	12.7a	2.4ab	-24.2b	50.7a	236.1ab
SmartQuatro	-22.4abc	-17.1ab	-8.1ab	37.5a	0.2a	-5.7b	7.5bc	11.4a	-6.9ab	-31.9c	16.8b	183.4b
MaxNPact	-27.5d	-17.8ab	-8.6ab	38.5a	9.4a	-4.1ab	3.6c	11.4a	-9.7b	-30.9c	7.5bc	186.8ab
Control	-26.8cd	-20.2b	-16.9b	35.0a	2.2a	-7.3b	6.2bc	5.0a	-5.9ab	-30.1bc	8.1bc	269.8a
LSD (0.10)	4.99	5.45	8.88	13.02	12.43	7.11	7.83	17.74	16.14	6.28	9.83	86.11

Dunn

Product	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B	Al
FertiRain	-10.0a	-9.3	-7.4	13.9	-20.9	-2.5	8.6	3.1	-0.4	-2.8	-11.8	72.2
SureK	-14.0a	-8.7	-6.3	15.7	-19.9	-0.5	7.8	15.2	7.6	-1.6	-9.3	45.3
HarvestMore	-15.7b	-5.1	-5.7	18.3	-21.4	-0.1	5.3	11.1	3.4	7.7	-13.6	28.0
SmartBMo	-12.3ab	-5.0	-9.6	16.8	-22.1	0.7	6.0	10.1	2.8	-8.3	-4.1	35.3
SmartQuatro	-14.2ab	-4.2	-6.0	22.4	-18.6	4.6	13.8	23.6	14.3	-6.0	-13.1	27.5
MaxNPact	-12.3ab	-8.4	-10.0	16.9	-24.1	-2.3	1.8	5.7	-4.8	-8.2	-14.4	15.2
Control	-13.9ab	-4.8	-3.7	20.9	-16.7	1.4	2.8	9.1	-5.1	-5.6	-11.2	2.5
LSD (0.10)	4.59	5.24	5.53	8.13	6.71	5.82	5.48	18.15	19.63	11.87	7.84	47.12

Table 13: Continued

Shawboro												
Product	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Al**
FertiRain	-5.4a	-6.3abc	-23.1a	26.6a	-3.5ab	-2.6ab	-12.3a	10.4b	16.0a	-4.4ab	-10.6b	185.6a
SureK	-6.2a	-8.3bc	-26.5a	53.4a	5.7a	-1.0ab	-10.1a	34.7a	21.2a	-4.5ab	-8.6b	32.9b
HarvestMore	-6.0a	-8.3bc	-26.6a	38.0a	-2.6ab	-2.9ab	-22.4a	25.0ab	22.2a	2.0a	-7.9b	56.7b
SmartBMo	-6.2a	-4.1ab	-21.4a	34.0a	-5.4b	-4.7ab	-12.1a	12.8ab	9.1a	-7.9ab	32.0a	-22.0b
SmartQuatro	-8.5a	-9.2c	-24.6a	32.7a	-1.1ab	-8.0b	-17.3a	16.2ab	14.8a	-10.0b	-11.3b	-6.8b
MaxNPact	-7.0a	-4.2ab	-22.9a	44.0a	-0.5ab	-3.1ab	-10.7a	20.7ab	19.1a	-5.1ab	-10.7b	8.5b
Control	-6.3a	-3.1a	-21.4a	45.3a	4.3ab	-0.4a	-19.5a	16.0ab	12.5a	-11.2b	-7.2b	-10.2b
LSD (0.10)	5.86	4.37	8.04	26.87	10.69	7.56	14.30	23.74	20.28	10.36	4.92	110.44

Suffolk												
Product	**N**	**P**	**K**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**	**B**	**Al**
FertiRain	-9.8a	-24.4a	-31.4a	54.7a	-20.2a	-10.1ab	4.1ab	26.4ab	6.9bc	1.8ab	-30.5b	75.7a
SureK	-10.5a	-28.3ab	-32.7ab	60.0a	-18.4a	-4.3a	6.5ab	18.8bc	-6.7d	-0.2bc	-30.2b	138.2a
HarvestMore	-14.9a	-24.5a	-33.8ab	57.0a	-18.1a	-6.0ab	7.1ab	27.6ab	7.0b	10.2a	-29.2b	80.1a
SmartBMo	-12.6a	-33.7b	-35.5b	54.6a	-25.2a	-11.6b	1.8b	-1.9c	-13.4d	-6.7bc	7.3a	150.6a
SmartQuatro	-13.0a	-25.7a	-33.5ab	64.1a	-17.4a	-7.9ab	8.4a	49.2a	20.6a	-7.7c	-28.5b	118.6a
MaxNPact	-14.7a	-27.6ab	-30.5a	59.5a	-22.9a	-7.3ab	4.7ab	25.8ab	-0.5bcd	-1.3bc	-29.2b	143.5a
Control	-11.4a	-28.8ab	-34.4ab	59.3a	-21.2a	-6.3ab	1.8b	18.6bc	-6.7cd	-3.2bc	-34.3b	103.7a
LSD (0.10)	6.45	6.85	3.92	14.04	8.05	5.98	6.35	27.36	13.23	8.61	6.57	109.82

*[a]Means followed by the same letters are not significantly different using Fisher's Protected LSD at *P*=0.10.

Table 14: Effects of foliar fertilization on soybean yield at all locations.

Product	Average Bu/A	Boonville Bu/A	Dunn Bu/A	Shawboro Bu/A	Suffolk Bu/A
FertiRain	57.8	26.9	66.7b	76.5ab	60.9
Sure K	57.5	26.9	70.0b	72.7c	62.4
HarvestMore	57.6	24.9	70.3ab	73.7bc	61.6
Smart B-Mo	58.1	25.9	70.3ab	76.1ab	60.0
Smart Quatro	58.2	27.3	67.1b	77.2a	61.1
MaxNPactK	56.7	25.7	66.0b	76.8a	58.4
Control	60.0	26.5	73.6a	77.2a	62.6
LSD (0.10)		2.45 (NS)	5.06	3.01	6.55 (NS)

Table 15: Critical values for plant tissue nutrient sufficiency ranges in ppm for flowering soybean.

Nutrient	Ranges
N	350-550
P	30-60
K	150-225
Ca	80-140
Mg	25-70
S	25-60
Fe	25-300
Mn	17-100
Zn	21-80
Cu	4-30
B	20-60

*Reference Sufficiency Ranges for Plant Analysis in the Southern Region of the United States, (Sabbe et al., 2013).

Table 16: Plant tissue nutrient sufficiency ranges in ppm.

	Interpretive categories			
Nutrient	**Likely response**	**Small probability of response**	**Sufficient range**	**Excessive or toxic**
N	<400	400-449	450-600	-
P	<25	25-34	35-55	>80
K	<170	170-199	200-300	-
S	<20	20-24	25-50	
Ca	<35	35-59	60-150	
Mg	<25	25-29	30-70	

Fe	<50	50-54	55-300	>500
Mn	<20	20-29	30-100	>200
Zn	<20	20-24	25-60	>75
Cu	<4	4-5	6-20	>50
B	<20	20-24	25-60	>80
Mo	<0.2	0.2-0.9	1.0-5.0	-
Al	-	-	<200	>400

*Plant Nutrient Analysis: Do your soybeans have the right stuff? (Mueller, 2019).

Table 17: Plant tissue nutrient sufficiency ranges in ppm.

	Interpretive categories				
Element	**Deficient**	**Low**	**Sufficient**	**High**	**Excess**
N	<400	400-450	450-550	551-700	>700
P	<15	16-25	26-50	50-80	>80
K	<125	126-170	171-250	251-275	>275
Ca	<20	21-35	36-200	201-300	>300
Mg	<10	11-25	26-100	101-150	>151
Mn	<14	15-20	21-100	101-250	>250
Fe	<30	31-50	51-350	350-500	>500
B	<10	11-20	21-55	56-80	>80
Cu	<4	5-9	10-30	31-50	>50
Zn	<10	11-20	21-50	50-75	>75
Mo	<0.4	0.5-0.9	1.0-5.0	5.1-10.0	>10
Al	-	-	<200	<201-400	>400

* Critical values used to classify a plant analysis of soybean leaves†, Ohio Plant Analysis Laboratory, 1965, by J.B. Jones Jr. (Hardy, 1967). † Upper fully mature trifoliate leaves sampled prior to pod set (w/o petiole).

Table 18: Average application rate, cost and loss of treatments.

Treatment Name	**Application Rate**	**Application Cost***
FertiRain	3 gal/A	$22.11/A
Sure-K	3 gal/A	$19.25/A
Smart B-Mo	1 pt/A	$3.82/A
Smart Quatro Plus	1 qt/A	$6.65/A
Maximum N-Pact K	1.5 gal/A	$21.25/A
HarvestMore UreaMate	2.5 lbs/A	$4.84/A
Untreated Control	-	$0.00/A

*Application cost is reflective of product cost at the applied rate only.